

**EXXON** RESEARCH AND ENGINEERING COMPANY

GOVERNMENT RESEARCH LABORATORIES

REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

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VOLUME 2

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February 18, 1976 - January 30, 1977

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 Government Research Laboratories  
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REDOX BULK ENERGY STORAGE SYSTEM STUDY

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Task IA  
Bibliography

Load Leveling and Peak Power Generation

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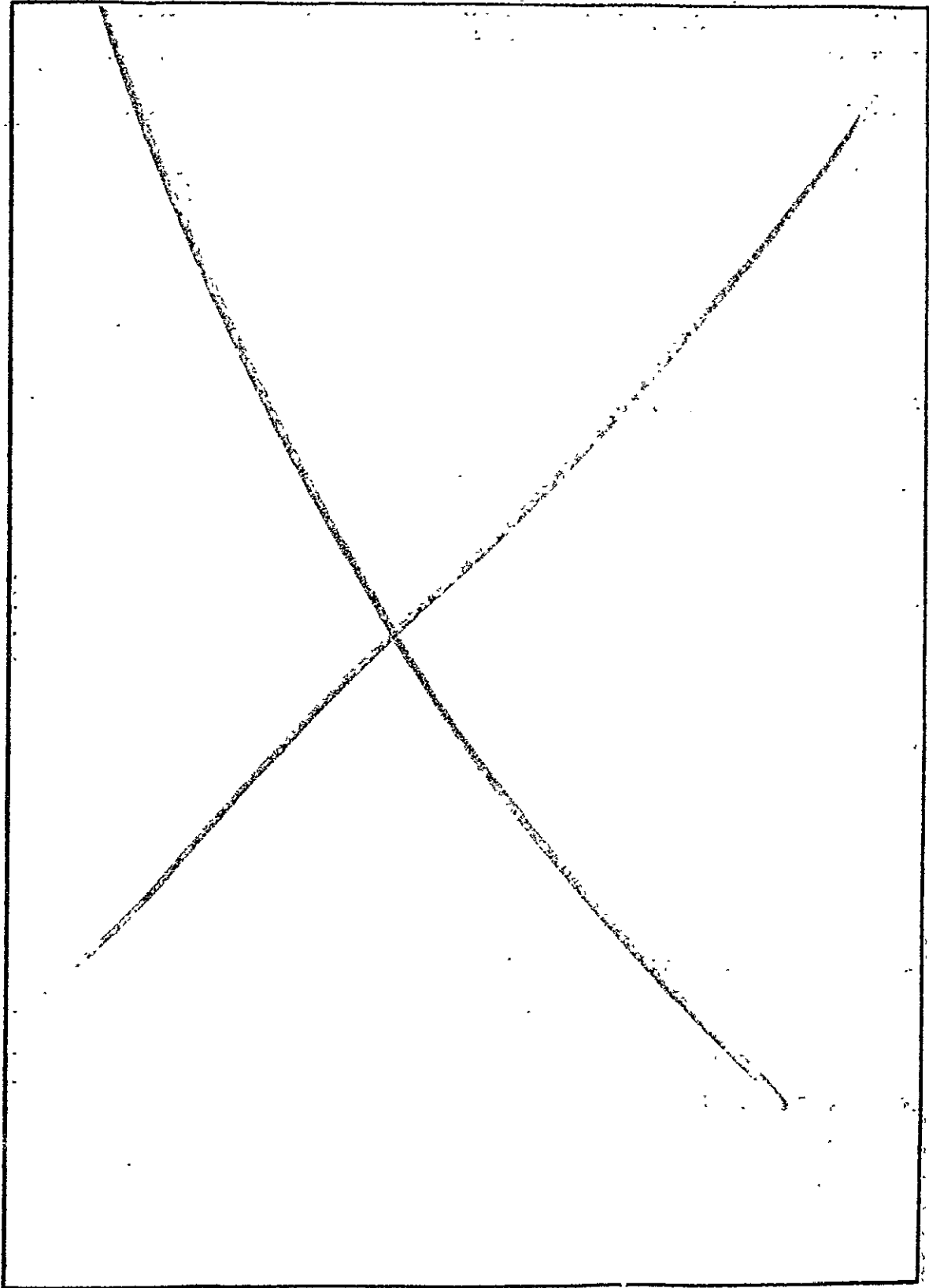
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  Volume 2 of this final report contains items delivered during the contract period, including a bibliography on load-levelling, a comparative assessment of electrochemical energy storage devices and documentation packages for several computer programs and Redox system models.		



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## FOREWARD

This document comprises Volume 2 of the final report on Redox Bulk Energy Storage System studies carried out under Contract No. NAS3-19776. Volume 2 is a compilation of the following items, delivered to NASA under terms of the contract.

- Task IA - Bibliography - Load Leveling and Peak Power Production
- Task IB - Comparative Analysis of Candidate Electrochemical Systems
- Task IIIA - Documentation for Stage 1 Model Computer Program
- Task IIIA - Documentation for Stage 1.5 Model Computer Program
- Task IIIB - Documentation for Stage 2 Model Computer Program

A comprehensive bibliography of available information and sources of information on load leveling and peaking power generation in the electric utility industries, has been assembled by Exxon Research and Engineering Company and Public Service Electric and Gas Company, within the constraints of time and money available.

The bibliography is presented in two sections. The first section presents the literature references in the above areas. These references have been given an alphabetical access number and identified as to subject and classification. The codes are shown in Tables 1 and 2.

A representative bibliographic display format is shown below:

<u>Alphabetical Access No.</u>	<u>Subject Classification</u>	<u>References</u>
B-26	1/GT	Brown, J.T. and Cronin, J.H., "Battery Systems for Peaking Power Generation," 1974 IECEC, p. 903 (August, 1974) (SAE Paper 749139)
W-7	1i/TUE	Walsh, W.J., Allen, J.W. et al, "Development of Prototype Lithium/Sulfur Cells for Application to Load-Leveling Devices in Electric Utilities," 1974 IECEC, p. 911 (August, 1974) (SAE Paper 749140)

The second-section presents the sources of current information on electric utilities. There are many general or survey articles on utility practices, requirements and future needs. However, specific data on individual utilities is available only in their submissions to the Federal Power Commission in Washington, D.C., as required by law. This data is available to any citizen. Other information is submitted by the utilities to trade organizations, such as the Edison Electric Institute. Access to this information is generally restricted to the individual members. Users of the bibliography could contact these organizations and, if a need to know could be demonstrated, access to the information could probably be obtained.

Table 1

Subject Index for Bibliography

Subject Areas

- |                             |                                     |
|-----------------------------|-------------------------------------|
| 0. Energy Storage           | 6. Refrigerated Fluids              |
| 1. Batteries                | 7. Hydrogen                         |
| a. Redox                    | 8. Economics                        |
| b. Lead-Acid                | 9. Electric Power and Energy Usage  |
| c. Ni/Cd                    | a. Current                          |
| d. Zn/A                     | b. Future                           |
| e. Zn/Halogen               | 10. Electric System Characteristics |
| f. Ni/Zn                    | (Load Generation)                   |
| g. Ni/H <sub>2</sub>        | a. Current                          |
| h. Na/S                     | b. Future                           |
| i. Li/S                     | 11. Load Management                 |
| j. Li/Cl                    | 12. Other Technology Implications   |
| k. Non Aqueous              | a. Solar Power                      |
| l. High Temperature         | b. Wind Power                       |
| m. Solid Electrolyte        | c. Nuclear Power                    |
| n. NaCl                     | d. Ocean Thermal                    |
| o. Other                    | e. Geothermal                       |
| 2. Pumped Hydro             | 13. Flywheels                       |
| a. Above Ground             | 14. Power Conditioning              |
| b. Below Ground             |                                     |
| 3. Compressed Air           |                                     |
| 4. Super Conducting Systems |                                     |
| 5. Thermal Storage          |                                     |
| a. Fused Salt               |                                     |
| b. Hot Oil                  |                                     |

Table 2

Classification Index for Bibliography

Classification Areas

A	Engineering Analysis
B	Bibliography
C	Costs
E	Economics
G	General
I	Impact Areas
M	Mathematical Analysis
O	Other
P	Electric Power Systems Statistics
R	Reviews
S	System and Process Analysis
T	Technology
U	Utility System Applications

SECTION 1

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AND

PEAKING POWER GENERATION

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A-5	3,7/G	Allen, K., "Eminence Dome--Natural-Gas Storage in Salt Comes of Age," J. Petroleum Technology, p. 1299 (November, 1972)
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A-7	5/TE	Altman, M. and Yeh, H., "Conservation and Better Utilization of Electric Power by Means of Thermal Energy Storage and Solar Heating: Executive Summary," Natl. Center for Energy Management and Power, Pa., NTIS Report PB-239,394, July 31, 1973 (31)
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B-55	2a,b/TA	Brennan, F.L., "Start-Up and Operating Performance, Northfield Mountain Pumped Storage Project," IEEE Meeting, New York, N.Y. (January 26-31, 1975)
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AN-75	2a,b/G	"Sweden's Energy Plans," Energy International, p. 29 (August, 1974)
AN-76	1/G	"Switching on Electric Vehicles," Environmental Science and Tech., <u>8</u> (410) (1974)
AN-77	10a/P	"T&D Construction," Electric World, <u>185</u> (6):49 (March 15, 1976)
AN-78	11/GU	"TEM Boosts Building's Energy Efficiency," Electrical World, <u>184</u> , p. 116 (September, 1975)
AN-79	9a,10a/P	Tennessee Valley Authority, "1975 Operations Municipal and Cooperative Distributors of TVA Power," Knoxville, Tennessee (1975)
AN-80	9a,10a/P	"1974 Year-End Summary of the Electric Power Situation in the United States," Edison Electric Institute, (December 31, 1974)

## AN-8

<u>Accession No.</u>	<u>Subject Classification</u>	<u>Reference</u>
AN-81	11/GU	"The How of Time of Day Pricing," AWARE Magazine, p. 7-12 (September, 1975)
AN-82	9a/P	"The Top 100 Electric Utilities-1974-A Year of Zero Growth," Electric Light & Power, <u>53</u> (7):7-11 (July 21, 1975)
AN-83	9a/P	"The Top 100 Electric Utilities 1974-A Year to Forget," Electric Light & Power, <u>53</u> (6):6-10 (June 23, 1975)
AN-84	9a/P	"The Top 100 Electric Utilities," Electric Light & Power, <u>52</u> (13):12-16 (July, 1974)
AN-85	0/G	"The U.S. Energy Problem," Intertechnology Rep C645 (November, 1971)
AN-86	9a/P	"Total Electric Utility Industry in the U.S.A. Including Alaska and Hawaii," Edison Electric Institute monthly publication, New York, New York (1976)
AN-87	3,7/G	"Underground Storage of Natural Gas in the United States," Compiled by Research Committee Interstate Oil Compact Commission (May 29, 1962)
AN-88	9a/P	"Uniform Statistical Reports," submitted annually by member companies to the Edison Electric Institute, New York, New York
AN-89	1/G	"Vehicle Symposium Scores Battery, Marketing Needs," Electric Light & Power, T/D Edition p. 52 (March, 1974)
AN-90	12b/GT	"Wind Energy," U.S. House of Representatives, 93rd Congress, 2nd Session (May, 1974)
AN-91	12b	"Wind Energy Conference," NASA-Lewis Research Center, Cleveland, Ohio (December, 1974)
AN-92	12b/GT	"Wind Energy Conversion Systems," Workshop Proceedings NSF/NASA, Washington, D.C. (June, 1973)

Accession No.	Subject Classification	Reference
AN-93	12b/RT	"Wind Power Electric Generator," The Engineer, p. 43 (July, 1955)
AN-94	12b/RT	"Wind Generated Electricity Prototype 100 KW Plant," Engineering, p. 370 (March, 1955)
AN-95	4/TGCA	"Wisconsin Superconductive Energy Storage Project, Volume I," University of Wisconsin Engineering Experiment Station (July, 1974)
AN-96	12c/G	"World Uranium Resources," Special Survey - Nuclear Engineering International, 20(225):95 (February, 1975)
AN-97	9a/P	"Statistics of Privately Owned Electric Utilities in the United States - 1973," Federal Power Commission, U.S. Printing Office, Washington, D.C. (1974)
AN-98	9a/P	"Statistics of Publicly Owned Electric Utilities in the United States - 1973," Federal Power Commission, U.S. Printing Office, Washington, D.C. (1974)
AN-99	9a,b/P	"Bulk Power Load and Supply Information Reported April, 1975 by the Regional Reliability Councils," FPC News, 8(24):2 (June 13, 1975)
AN-100	10a,b/P	"Bulk Power Load and Supply Information," FPC News, 8(27):2 (July 4, 1975)
AN-101	9b/P	"Bulk Power Load and Supply Projections for 1985-1994," FPC News, 8(49):2 (December 5, 1975)
AN-102	10b/P	"Proposed Generating Capacity Additions 1975-1984," FPC News, 8(50):2 (December 12, 1975)
AN-103	9a/P	"Staff Report on 1975 Summer Load Power Supply Situation Contiguous United States," FPC News, 8(24):1 (June 13, 1975)
AN-104	9a/P	"Staff Report of 1975-76 Winter Load Power Supply Situation Contiguous United States," FPC News, 8(49):9 (December 5, 1975)

<u>Accession No.</u>	<u>Subject Classification</u>	<u>Reference</u>
AN-105	9a/P	"Electric Power Statistics," Federal Power Commission (monthly publication), U.S. Printing Office, Washington, D.C. (March, 1974)
AN-106	9a/P	"Sales of Firm Electric Power for Resale 1968-1972," Federal Power Commission, U.S. Printing Office, Washington, D.C. (March, 1974)
AN-107	9a/P	"Performance Profiles-Private Electric Utilities in the United States 1963-1970," Federal Power Commission, U.S. Printing Office, Washington, D.C. (1973)
AN-108	9a,b/P 10a,b/P	"1970 National Power Survey, Parts I through IV," Federal Power Commission, U.S. Printing Office, Washington, D.C. (December, 1971)
AN-109	9a,b/P 10a,b/P	"Electric Power in South Central Region 1970-80-90," South Central Region Advisory Commission, FPC Report (February, 1969)
AN-110	9a,b/P 10a,b/P	"Electric Power in Southeast 1970-80-90," Southeast Region Advisory Commission, FPC Report (April, 1969)
AN-111	9a,b/P 10a,b/P	"Future of Power in West Region 1970-80-90," West Regional Advisory Commission, FPD Report (June, 1969)
AN-112	9a,b/P 10a,b/P	"Electric Power in the East Central Region 1970-80-90," East Central Regional Advisory Commission, FPC Report (December, 1969)
AN-113	9a,b/P 10a,b/P	"West Central Region Power Survey 1970-80-90," West Central Regional Advisory Commission, FPC Report (1969)
AN-114	9a,b/P 10a,b/P	"Alaska Power Survey," Federal Power Commission, U.S. Printing Office, Washington, D.C., FPC Report (1969)
AN-115	9a,b/P 10a,b/P	"Electric Power in the Northeast 1970-80-90," Northeast Regional Advisory Commission, FPC Report (1968)
AN-116	12c/P	"Nuclear Survey: Cancellations and Delays," Electrical World, <u>184</u> (8):35-44 (October 15, 1975)

## SECTION 2

### ELECTRIC UTILITY .DATA SOURCES

The National Electric Reliability Council (NERC) was formed voluntarily by the electric utility industry in 1968 and directs its efforts to augment the reliability and adequacy of bulk power supply of the electric utility systems in North America. NERC consists of nine regional reliability councils whose memberships comprise essentially all of the electric power systems in the United States and the Canadian systems in the provinces of Ontario, British Columbia, Manitoba, and New Brunswick. The nine councils are:

1. ECAR East Central Area Reliability  
Coordination Agreement
2. ERCOT Electric Reliability Council  
of Texas
3. MAAC Mid-Atlantic Area Council
4. MAIN Mid-America Interpool Newark
5. MARCA Mid-Continent Area Reliability  
Coordination Agreement
6. NPCC Northeast Power Coordinating Council
7. SERC Southeastern Electric  
Reliability Council
8. SPP Southwest Power Pool
9. WSCC Western Systems  
Coordinating Council

NERC publishes annual reports which give the highlights of the activities of NERC during the year and comments on the progress and problems relating to the reliability and adequacy of bulk power supply in the electric utility systems in North America.

In response to Federal Power Commission Order 383-3, Docket No. R-362, each reliability council is required to file Systems Plans each year. As an example of the type of data contained in these reports, the table of contents and the introduction of the MAAC System Plan filed on April 1, 1975 is attached.

National Electric Reliability Council Reports are available at the Federal Power Commission or from NERC Headquarters located in Princeton, New Jersey. FPC statistical reports are based on the information provided by NERC.



MAAC SYSTEM PLANS

(as of December 31, 1974)

Response to Federal Power Commission Order 383-3,

Docket No. R-362 required to be filed by

April 1, 1975

## TABLE OF CONTENTS

### INTRODUCTION

#### Section I - NET LOADS

- A. Estimate of Monthly Peaks (1975 and 1976)
- B. Estimate of Monthly Net and Gross Energy Requirements (1975 and 1976)
- C. Estimate of Summer and Winter Peak Loads (1977 through 1984)
- D. Estimate of Annual Net and Gross Energy Requirements (1977 through 1984)

#### Section II - GENERATION

- A. Existing Capacity Resources (December 31, 1974)
- B. New Capacity Resources or Retirements
- C. Capacity Exchanges between MAAC and Other Councils

#### Section III - CAPACITY MARGINS FOR RESERVES

- A. Load and Capacity Tabulation (Summer and Winter)
- B. Assessment of Adequacy of Reserves
- C. Statement of Criteria Used in Determining Reserve Requirements

#### Section IV - STATUS REPORT ON ENVIRONMENTAL CONTROLS FOR STEAM GENERATION ADDITIONS OF 300 MW OR MORE

#### Section V - A PLAN OF THE BULK POWER TRANSMISSION NETWORK

- A. Map of System for Summer of 1975
- B. Map of System Projected to Summer 1980
- C. Map of System Projected to Summer 1984
- D. Tentative Transmission Additions Through 1980

Section VI - LOAD FLOW AND STABILITY STUDIES

A. Load Flow Studies

- (1) 1975 and 1980 Base Case Diagrams
- (2) Transfer Capability for 1975 and 1980
- (3) Index of Contingencies

B. Stability

- (1) Index of Contingencies Showing Swing Curves for Some Units
- (2) Statement of Network Stability Criteria

Section VII - DESCRIPTION OF THE PRINCIPAL COMMUNICATION AND CONTROL SYSTEMS

Section VIII - STATUS REPORT OF CONSULTATIONS AFFECTING CONSTRUCTION OF TRANSMISSION LINES 230 KV OR HIGHER

- A. Evaluation of Impact of Delays and Changes in Plans of Transmission Facilities on the Reliability of the Region
- B. Status Report of Consultations for all Lines 230 kV and Higher

Section IX - COORDINATED REGIONAL PRACTICES

Section X - LOAD AND CAPACITY PROJECTION - 1985 THROUGH 1994

Section XI - SYSTEM DIAGRAMS FOR 1984 AND 1994

- A. Map of System Projected to Summer of 1984
- B. Planned Voltage Levels
- C. A Diagram of a MAAC UHV. Transmission Pattern for 1994
- D. A Diagram of a MAAC HVDC Development for 1994
- E. A Diagram of a MAAC Continued Development of 500 kV for 1994

## MAAC SYSTEMS PLANS

### INTRODUCTION

The companies composing the Mid-Atlantic Area Council participate in coordinated planning of their generation and transmission facilities in order to improve the reliability and adequacy of the bulk power system.

The following electric systems are signatories under the MAAC Coordination Agreement:

- Atlantic City Electric Company
- Baltimore Gas and Electric Company
- Delmarva Power & Light Company
- Jersey Central Power & Light
- Metropolitan Edison Company
- Pennsylvania Electric Company
- Pennsylvania Power & Light Company
- Philadelphia Electric Company
- Potomac Electric Power Company
- Public Service Electric & Gas Company
- UGI Corporation

Associates Include:

- Allegheny Electric Cooperative representing the  
Pennsylvania and New Jersey Cooperatives
- The Easton Utilities Commission representing  
Maryland Municipals
- The City of Vineland Electric Utility representing  
New Jersey Municipals

The MAAC Executive Board is authorized to act in the administration of all matters pertaining to the Agreement. The systems listed above as MAAC Associates represent the interests of municipals and electric cooperatives.

The interconnected bulk electric supply system of the signatories of the MAAC Coordination Agreement is operated on a fully coordinated basis as the Pennsylvania-New Jersey-Maryland Interconnection (PJM).

The information presented in this report represents historical data through December 31, 1974. Estimates projected for the ten-year reporting period through 1984 are the Systems' best judgment.

## II. Edison Electric Institute (EEI)

The Edison Electric Institute consists of approximately 180 privately owned member electric utilities. Every year each utility submits a Uniform Statistical Report (USR) to the EEI for the purpose of providing general and statistical information about the utility. The attached copy of the table of contents shows the type of information contained in the USR reports.

The Edison Electric Institute is located in New York City. The USR reports which are filed there are not available to the general public. However, these reports can be accessed with permission of the EEI.

# UNIFORM STATISTICAL REPORT—YEAR ENDED DECEMBER 31, 1971

(To American Gas Association, Edison Electric Institute and Financial Analysts)

Please submit the required pages, together with a copy of the Company's Annual Report to Stockholders, by April 1, to the American Gas Association and/or the Edison Electric Institute. A copy of the Company's Annual Report to Stockholders may be submitted after that date if not available at the time this report is mailed. If such report does not show capitalization by issues, furnish this information on a supplemental page.

All Energy and Dollar Amounts should be reported in Thousands. Because this report is frequently used in conjunction with the Company's Annual Report to Stockholders, the data included herein should agree with the comparable information in such Annual Report. To assure accuracy and consistency, numerous cross-ties and footnotes have been appended to the schedules so that the statistics for the same item shown on more than one schedule will be identical.

## Name and Address of Company

PUBLIC SERVICE ELECTRIC AND GAS COMPANY  
80 Park Place  
Newark, New Jersey 07101

## List Affiliated Companies and Indicate Relationship (Parent, Subsidiary, Associate, etc.)

TRANSPORT OF NEW JERSEY  
(Unconsolidated subsidiary; not  
included in this report)

## Individual Furnishing Information

Name A. F. Kull  
Title Statistician  
Telephone No. 201 - 622-7000 Ext. 2900

April 17, 1972  
Date This Report Released

THIS REPORT HAS BEEN PREPARED FOR THE PURPOSE OF PROVIDING GENERAL AND STATISTICAL INFORMATION CONCERNING THE COMPANY AND NOT IN CONNECTION WITH ANY SALE, OFFER FOR SALE OR SOLICITATION OF AN OFFER TO BUY ANY SECURITIES.

- 9 -  
UNIFORM STATISTICAL REPORT — YEAR ENDED DECEMBER 31, 1971

Company PUBLIC SERVICE ELECTRIC AND GAS COMPANY

**TABLE OF CONTENTS  
ELECTRIC AND GAS**

	<u>Schedule</u>	<u>Page</u>
<b>I. GENERAL STATISTICS</b>		
States in which company operates and percent of Operating Revenue by States		
Subsidiaries and Leased Companies		
Utility Systems Acquired, Sold or Otherwise Disposed of		
Changes in Communities Served		
Population and Square Miles of Territory Served		
<b>II. FINANCIAL AND ACCOUNTING STATISTICS</b>		
Statements of Income and Retained Earnings	II	2
Notes to Statements of Income and Retained Earnings	III	3
Functional Details of Operation and Maintenance Expenses	IV	5
Taxes	V	6
Balance Sheet	VI	7
Notes to Balance Sheet	VII	8
Utility Plant by Functional Accounts	VIII	9
Notes to Utility Plant by Functional Accounts	IX	10
Additions, Retirements and Adjustments to Utility Plant	X	10
New Securities Issued	XI	11
Statement of Changes in Financial Position	XII	12
<b>III. EMPLOYEE STATISTICS</b>	XIII	13
Number of Employees		
Salaries and Wages		
Pensions and Benefits		
<b>IV. OPERATING STATISTICS — ELECTRIC</b>		
Classification of Sales, Revenues and Customers	XIV	E-14
Classification of Industrial (or Large Light and Power) Sales and Revenues	XV	E-15
Source and Disposal of Energy	XVI	E-16
Maximum Demands and Net Capability at Time of Company Peaks	XVII	E-17
<b>V. GENERATING STATION STATISTICS — ELECTRIC</b>		
Generating Station Statistics	XVIII	E-18
Fuel Consumed for Generation	XIX	E-19
Efficiency of Steam Generating Units	XX	E-19
Generating Units Retired, Added, Under Construction or Authorized	XXI	E-20
<b>VI. OTHER PHYSICAL STATISTICS — ELECTRIC</b>	XXII	E-21
Transmission Lines		
Distribution Lines		
Substations and Line Transformers		
<b>VII. OPERATING STATISTICS — GAS</b>		
Gas Supply and Disposition	XIV	G-14
Solid and Liquid Fuels Used and By-Products Recovered	XV	G-15
List of Gas Purchases	XVI	G-15
Sales for Resale	XVII	G-16
Transported for Others	XVIII	G-16
Used for Electric Generation	XIX	G-16
Classification of Sales, Revenues and Customers	XX	G-17
Classification of Large Volume Sales and Revenues	XXI	G-18
Daily Gas Availability and Requirements	XXII	G-19
Heating Degree Days	XXIII	G-19
<b>VIII. FACILITIES STATISTICS — GAS</b>		
Underground Storage Data	XXIV	G-19
Liquefied Natural Gas Data	XXV	G-19
Miles of Pipeline and Compressor Station Data	XXVI	G-20

### III. Federal Power Commission (FPC)

The Federal Power Commission requires utilities to complete a number of forms as shown on the attached sheet. Of these forms, Form No. 12 contains the most comprehensive electric load and capacity data. The attachment lists the type of data reported on Form No. 12.

Federal Power Commission forms are kept on file at its headquarters located in Washington, D.C. All forms can be accessed by the general public.



F.P.C. FORMS DECEMBER 1, 1975

F.P.C.  
Form No.

Description

1	Annual Report for Electric Utilities (Class A and B) (Prepared by Gen. Acctg., Filed by Stat. via Law Dept.)
1F	Annual Report for Public Utilities (Class C and D)
1M	Annual Report for Municipal Electric Utilities (Revenue over \$250,000)
2	Annual Report for Natural Gas Companies (Class A and B)
2A	Annual Report for Natural Gas Companies (Class C and D)
3	Typical Net Monthly Bills (Prepared annually by Rates Dept., Filed by Stat. Dept.)
3P	Monthly Electric Bills (for Bureau of Labor Statistics) (Prepared monthly by Rates Dept., filed by Stat. Dept.)
4	Monthly Report of Generation and Fuel Stocks (multiple plant utilities) (Prepared by Electric Prod. Dept., Filed by Stat. Dept.)
4A	Monthly Report of Generation and Fuel Stocks (single plant utilities)
4B	Monthly Report of Industrial Generation
5	Monthly Statement of Electric Operating Revenue and Income (Prepared by Gen. Acctg., filed by Stat. Dept.)
6	Initial Cost Statement for Licensed Projects (Prepared and filed by J.C.P. & L. Co.)
7	Statement of Actual Legitimate Cost of Construction (Prepared and filed by J.C.P. & L. Co.)
8	Report of Gas Stored Underground
9	Annual Report for Licensees of Privately Owned Major Projects (Prepared and filed by J.C.P. & L. Co.)
11-	Natural Gas Pipeline Company monthly statement
12	Power System Statement for Class I and II Systems (Material supplied by Production and T. & D. Depts., prepared and filed by Stat. Department via Law Dept.)
12A	Power System Statement for Class III, IV and V Systems
12B	Industrial Electric Generating Capacity (detailed)
12C	Industrial Electric Generating Capacity (limited)
12D	Power System Statement for Class III Systems
12E-1	Monthly Power Statement for Class I and II Systems (Prepared by Production and T. & D. Depts., checked, typed and filed by Stat. Dept.)
12F	Power Line and Generating Plant Data (Prepared and filed by T. & D. Dept.)
13	Summary for National Electric Rate Book (Prepared and filed by Rates Dept.)
14	Annual Report for Importers and Exporters of Natural Gas
15	Annual Report of Gas Supply of Certain Natural Gas Companies
15A	Annual Report of Gas Supply of Certain Natural Gas Companies (exempt from certain requirements.)
16	Report of Gas Supply and Requirements
23B	Quarterly Electric Utility Generation and Fuel Planning Report (Quarterly projection of estimated generation and fuel requirements) (Prepared and filed by Production Dept.)
40	Natural Gas Companies Annual Report of Proved Domestic Reserves
45	Reporting of New Nonjurisdictional Sales of Natural Gas
67	Steam-Electric Plant Air and Water Quality Control Data (Prepared by Electric Production Dept., checked by Stat. Dept., filed by Law Dept.)
69	Report of Alternate Fuel Demand Due to Natural Gas Curtailments
80	License Projects Recreation Report (Prepared and filed by J.C.P. & L. Co.)
82	Report of Changes in Retail Rates (Prepared and filed by Rates Dept.)
237A	Weekly Fuel Emergency Report Form (Coal) (Filed only during periods of emergency by Production Dept.)
237B	Weekly Fuel Emergency Report Form (Oil) (Filed only during periods of emergency by Production Dept.)
301A	Statement of Sales and Revenues of Independent Producers (under 2 million MCF/year)
301B	Statement of Sales and Revenues of Independent Producers (over 2 million MCF/year)
423	Monthly Report of Cost and Quality of Fuel for Steam - Electric Plant (Prepared and filed by Fuel Supply Dept.)

In addition, there are various other reports to be filed with the F.P.C., usually to report emergency interruptions of service and that sort of matter.

# POWER SYSTEM STATEMENT

For the Year Ended December 31, 1973

MADE BY

PUBLIC SERVICE ELECTRIC AND GAS COMPANY  
(Full legal name of respondent)

80 PARK PLACE, NEWARK, NEW JERSEY 07101  
(Address)

COVERING

PUBLIC SERVICE ELECTRIC AND GAS COMPANY  
(Common designation of system)

TO THE

FEDERAL POWER COMMISSION

*The following is an excerpt from the Commission's regulations prescribing the filing of Power System Statements for Electric Utilities, Licensees, and Others.*

## Part 141—Statements and Reports (Schedules)

\* \* \* \*

§ 141.51 Form No. 12, Power system statements for Class I and II systems and for Class IV and V systems where requested.

(a) The revised FPC Form No. 12 Power System Statement (Class I, II, IV and V Systems), including the revised instructions and schedules therein contained, be and the same hereby is approved and adopted.

(b) Each corporation, person, agency, authority or other legal entity or instrumentality, whether public or private, which operates facilities for the generation or transmission, or distribution of electric energy, and which is in the classification of Class I or Class II Systems or is in the classification

of Class IV or V Systems, where Form No. 12 is requested (as such classes are defined in the accompanying revised FPC Form No. 12), shall hereafter annually prepare and file with the Commission on or before the 1st of May of 1956, and each year thereafter, such statement or statements, and in such form as is required by said instructions and schedules, setting forth the answers to the questions therein stated, and furnishing the information therein called for, for the preceding calendar year.

\* \* \* \*

The revised form was prescribed by the Commission by Order No. 183, issued January 14, 1956 (15 FPC 790) and amended by Order No. 224, issued Sept 15, 1960 (24 FPC 460) and Order No 312, issued December 20, 1965. Statutory authority for the Commission's action is granted by the Federal Power Act, as amended (49 Stat. 838, 16 U.S.C. 791a-825r) and particularly Sections 4(a), 301(a), 302(b), 303, 304, 309 and 311 (49 Stat 839, 854, 855, 858, 859; 16 U.S.C. 797(a), 825(a), 825a(b), 825b, 825c, 825h, 825j).

## DEFINITIONS

1. "Person," as hereinafter used, means a corporation or person, as defined in section 3 of the Federal Power Act, agency, authority, or other legal entity or instrumentality, whether public or private, including a municipality as defined in said section 3.
2. "System," as hereinafter used, means all physically connected electric generating and/or transmission and/or distribution facilities operated as a unit under one control, management, or operating supervision by one or more persons.
3. "Respondent," as hereinafter used, means the person or persons upon whose behalf a power system statement is filed.
4. The "net energy for system" (entered on line 7 of schedule 9) is the sum of system net generation and energy received from others less the energy delivered to others for resale.
5. The "capability" of a generating plant is defined as its load-carrying ability at the specified power factor and indicated time interval independent of the other characteristics of the load.  
In general, a plant's capability is determined by design characteristics; physical condition; adequacy of the prime mover; prime mover steam supply; operational limitations, such as cooling and circulating water supply and temperature, ambient temperature; and head and tailwater elevations.
6. The "dependable capacity" of a generating plant or groups of plants is defined as the load-carrying ability for the time interval and period specified when related to the characteristics of the load to be supplied.  
In general, a plant's dependable capacity is influenced not only by factors affecting its capability, but by such factors as the duration of the system peak, position on the load curve where the plant is to be operated, and the plant's operating power factor.
7. "Demand interval" is the period of time over which the demand is measured. Each system shall report load data on the basis of integrated demands for 60-minute clock-hour intervals. Where demand data are not available on this basis, it is desired that adjustments be made to approximate the integrated demand for 60-minute clock-hour intervals and explained in footnotes. Where such adjustment cannot be made, demand data should be furnished in the form available and explained in footnotes.
8. The terms "hydro" and "hydroelectric" for purposes of this statement refer to conventional hydroelectric plants.

## GENERAL INSTRUCTIONS

Statements concerning the operation of electric power systems as required by the Commission's order, shown on page 1, should be prepared and filed in conformity with the following requirements, unless otherwise directed by the Regional Office of the Federal Power Commission:

1. Where a person operates a system and only one system, one statement should be filed for that system;
2. Where a person operates more than one system, separate statements should be filed for each system so operated.
3. Where more than one person operates a system, either a consolidated statement should be filed upon behalf of all, or separate statements should be filed by each, as directed by the Regional Office of the Federal Power Commission.
4. Where several systems, filing separate reports, are operated under some form of power pool operation or common dispatching, a supplementary power system statement on F. P. C. Form No. 12 covering the pool operations should also be filed, including a brief statement describing the method of operation under the power pool arrangement.
5. Scope of the statement.

Basis of Classification	Class of System	Scope of Statement
Systems which generate all or part of system requirements and whose net energy for system for the year covered by this statement was—		
More than 100,000,000 kilowatt-hours .....	I	Form No. 12 complete.
20,000,000 to 100,000,000 kilowatt-hours .....	II	Form No. 12 complete, excepting schedule 15.
5,000,000 to 20,000,000 kilowatt-hours .....	III	Form No. 12-A.
Less than 5,000,000 kilowatt-hours .....	III	Form No. 12-D.
Systems engaged primarily in sales for resale and/or sales to industrials, all other sales being negligible .....	IV	
Systems which obtain entire energy requirements from other systems .....	V	Form No. 12-A unless Form No. 12 or No. 12-D is requested.

6. Six signed copies of the completed statement, including the original if the report is typewritten, shall be returned to the Regional Office of the Federal Power Commission at the address shown on the front of the cover supplied by the Commission.
7. All communications concerning this statement and all requests for extra copies of individual pages should be addressed to the Regional Office of the Commission. Additional covers or copies of the complete form may be obtained from the Federal Power Commission, Washington, D. C., at 15 cents and 75 cents per copy, respectively.
8. Entries on this form may be made by typewriter, with pen and ink, or by any suitable method to facilitate reproduction, provided the entries are legible and in proper alignment.
9. Before the statement is prepared in final form for return to the Commission, all figures on the working copy should be checked for mathematical accuracy and for consistency, where the same figures appear in more than one schedule in this or in other statements or reports submitted to the Federal Power Commission. Any apparent inconsistency should be explained.
10. No deviation from these instructions should be undertaken without the approval of the Regional Office of the Federal Power Commission.
11. Insert the word "none" where it is a true and complete answer to any particular inquiry. Insert the words "not applicable" in those schedules or parts of schedules which do not apply to the respondent's system.
12. Where exact data are not available, report estimated data and designate such entries by the abbreviation "Est."
13. All information shall be furnished for the calendar year.
14. All information is to be furnished for the system as it existed at the end of the year. In case part of the system was acquired by the respondent during the calendar year, the respondent should report this part for the entire year, obtaining the necessary information from the records of the previous owners. In case part of the system was disposed of during the calendar year and the respondent was not operating that part at the end of the year, the respondent should not report on this part at all.

FORM 12

- Schedule 1 - Capacity and Output of System Generating Plants
- Schedule 2 - System Hydroelectric Data
- Schedule 3 - Plant Data - Small Plants
- Schedule 4 - Hydroelectric Plant Data
- Schedule 4A - Pumped Storage Plant Data
- Schedule 5 - Steam-Electric, Including Nuclear, Plant Data
- Schedule 7 - Internal-Combustion Engine and Gas Turbine Plant Data
- Schedule 8 - Itemized Accounting of Energy Transfers with Other Electric Utility Systems and Industrial Companies During the Year
- Schedule 9 - System Energy Accounting for the Year
- Schedule 10 - Energy Delivered to Ultimate Consumers
- Schedule 11 - Energy Transferred To or Across a State Line or In International Boundary During the Year
- Schedule 13 - Demand on Generating Plants, Power Received, and Power Delivered, For Resale, at the Time of System Peak Load of the Year
- Schedule 14 - Net Generation, Energy Received and Delivered and System Peaks by Months for the Year
- Schedule 15 - System Load Data for Specified Weeks
- Schedule 16 - System Dependable and Assured Capacity
- Schedule 16B - Future Changes in Capacity
- Schedule 17 - Distribution of System Load in Service Area
- Schedule 18 - System Maps and Diagrams
- Schedule 19 - Summer and Winter Peak Months and Calendar Year Load Estimates

**EXXON** RESEARCH AND ENGINEERING COMPANY  
GOVERNMENT RESEARCH LABORATORIES

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REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

Task IB

Comparative Analysis of  
Candidate Electrochemical Systems

By

Exxon Research and Engineering Company  
Government Research Laboratories  
1900 East Linden Avenue  
Linden, New Jersey 07036

P. Grimes

Prepared for

NASA-Lewis Research Center  
Cleveland, Ohio 44135

July 30, 1976

**government  
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## TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION . . . . .	1
2. ELECTROCHEMICAL CANDIDATE SYSTEMS FOR BULK ENERGY STORAGE. . . . .	8
2.1 Lead-Acid Batteries . . . . .	35
2.2 Zinc-Air Batteries. . . . .	45
2.3 Nickel-Zinc Batteries . . . . .	52
2.4 Nickel-Hydrogen Batteries . . . . .	56
2.5 Zinc-Chloride Batteries . . . . .	62
2.6 Sodium-Sulfur Battery Systems . . . . .	71
2.7 Lithium-Chlorine Batteries. . . . .	79
2.8 Lithium-Sulfur Batteries. . . . .	81
2.9 Organic Electrolyte Secondary Batteries . . . . .	85
2.10 Summary . . . . .	88
3. MATERIALS AVAILABILITY, SALVAGE AND MANUFACTURE. . . . .	91
3.1 Introduction . . . . .	91
3.2 Lead-Acid Batteries . . . . .	91
3.3 Zinc-Chlorine Hydrate Batteries . . . . .	92
3.4 Sodium-Sulfur Batteries . . . . .	92
3.5 Lithium-Metal Sulfide Batteries . . . . .	93
3.6 Zinc-Air Batteries. . . . .	93
3.7 Manufacturability . . . . .	93
4. BATTERY OPERATION AT CONSTANT POWER. . . . .	94
5. POWER CONDITIONING . . . . .	112
6. ENVIRONMENTAL IMPACT AND SAFETY CONSIDERATIONS . . . . .	124

## 1. INTRODUCTION

The storage of off-peak electric power (and the storage of electrical energy from solar energy systems) is an area of vital concern now and in the near future.

Among the methods of energy storage, batteries provide probably the best near-term answer. A survey of electric utilities indicated that batteries were the overwhelming choice (1)\*. This survey is shown in Table 1-1.

However, in the real world, batteries must compete against other alternative methods of supplying electrical energy to the ac networks. In this choice, the capital and operating cost of the alternatives, such as peaking gas turbines, above-ground pumped hydro, combined gas turbine steam turbine cycles, etc., must be weighed against the cost of energy storage system. What is an affordable price for batteries? A recent EPRI study (1) indicated that battery energy storage systems costing in the range of \$20/kwh for storage and \$80/kw for power conversion equipment would be competitive against gas turbine generators, operating three hours a day, 250 days per year. If credits of \$60/kw (for siting, transmission and distribution savings, etc.) can be applied, the above batteries would be competitive against gas turbine on a ten hour per day, 250 days per year basis. The question of credits is complex, however, requiring detailed analysis and will vary from utility to utility. Many factors enter into the utilities choice of energy systems, but it is evident that batteries and conversion equipment must be low in cost to be competitive.

Lead-acid batteries are the first choice for consideration for a battery energy storage system. They have a long history of proven reliable service. In addition, they have a known technology, manufacturability and are available now.

EPRI, ERDA and ILZRO (International Lead Zinc Research Organization) initiated a study of state-of-the-art lead-acid batteries especially designed for load-leveling applications and to be manufactured on a large scale. ESB, C&D and Gould, three of the largest lead-acid manufacturers, designed such batteries and considered the manufacturing problem (1-3). A summary of their results is given in Table 1-2. While the technical specifications would be acceptable to the utilities, the costs of these long cycle life batteries are too high.

Estimates of the installed costs for the lead-acid battery energy storage systems are given in Table 1-3 (1). In this case, only the short-time peaking operation (3-5 hours) has any possibility of economic viability.

-----  
\*References are given at the end of each subsection.

Table 1-1  
Priorities for Energy Storage

<u>TECHNOLOGY</u>	NUMBER OF UTILITIES RESPONDING			
	<u>FAVORABLE</u>	<u>MARGINAL</u>	<u>POOR</u>	<u>TOTAL</u>
Batteries	19	9	3	16
Compressed Air	12	13	4	8.5
Thermal (After Meter)	15	5	9	6.4
Underground Pumped Hydro	10	10	9	1.1
Flywheels	6	10	13	-7.5
Thermal (Before Meter)	4	10	13	-10
Superconducting Magnetic Energy (SMES)	1	5	15	-21

Total is computed by allowing one point for favorable rating, zero for marginal, and minus one for poor and then adding. The answer is normalized to same base number of responses (31).



Table 1-2

Capital Costs And Specifications  
For Utility Lead-Acid Batteries  
(Ten-Hour Capacity)

<u>COST/SPECIFICATION</u> <sup>(1)</sup>	---- BATTERY SYSTEM-----			
	<u>C&amp;D</u>	<u>ESB</u>	<u>GOULD</u>	<u>SLI</u> <sup>(2)</sup>
Lead Cost (\$/kWh)	22.10	19.80	13.00	9.60
Other Materials Costs (\$/kWh)	11.70	14.40	10.70	4.40
Price (\$/kWh) <sup>(3)</sup>	62.90	65-70	43.30	28.10
Cycle Life (cycles) (years)	2500 10	2500 10	1750 7	100-150 <sup>(5)</sup> --
Price/Cycle (¢/kWh/cycles)	2.51	2.60	2.47	2.3
Depth of Discharge (10-hr rate)	72	80	80	80
Plate Design	pasted	tubular	pasted	pasted
Efficiency (%) <sup>(4)</sup>	83	82	80	--
Cell Capacity (kWh)	20	19	125 <sup>(6)</sup>	--
Energy Density (WH/lb)	7.5	8.6	8.9	--
Footprint (kWh/ft <sup>2</sup> )	4.6	5.0	4.0	--

(1) Costs are based upon rated or end-of-life capacity.

(2) Based upon discussions with Warren Towle of Globe Union, Dec. 1975.

(3) Assumes 1000 MWh/year of sales.

(4) Ten-hour discharge and 7-hour charge with additional 3-hr taper charge.

(5) Can be improved with little additional cost to achieve 250-300 cycles.

(6) Open-tank concept.

Table 1-3

Lead-Acid Battery Plant Costs

<u>Item</u>	<u>Cost</u>	PLANT COST (\$/kW of nominal output)		
		<u>3 Hour</u> <sup>(1)</sup>	<u>5 Hour</u> <sup>(1)</sup>	<u>10 Hour</u>
Battery	\$57-70/kWh <sup>(2)</sup>	220-270	320-400	570-700
Convertors	\$70/kW	70	70	140 <sup>(3)</sup>
Cooling <sup>(4)</sup>	\$5-8/kWh	20-30	30-45	50-80
Site/Engineering	\$20-35/kWh <sup>(5)</sup>	<u>80-140</u>	<u>110-200</u>	<u>200-350</u>
TOTAL <sup>(6)</sup>		390-510	530-715	960-1270

- (1) The energy-related costs for the 3- and 5-hour battery are 1.30 and 1.15 times those of the 10-hour battery. However, these factors might approach 1.15 and 1.0, respectively, if the battery were specifically designed for this application and if the battery were used fewer than 250 cycles/year.
- (2) Gould's battery price of \$43.30/kWh (see Table IV) is increased to include "up-front" money for refurbishments, making it a 21-year battery (as compared to a 10-year battery for the other manufacturers).
- (3) Power is controlled by the 7-hour charge, not the 10-hour discharge.
- (4) Optional for Gould battery as presently conceived.
- (5) Lower limit is a rough estimate; and upper value is from a study by Bechtel for ERDA. Gould has estimated \$27/kWh. Estimates as low as \$10/kWh has been projected by others.
- (6) Total has to be divided by the one-way efficiency of the convertors (c.a. 94-95%).

It is obvious that lower cost batteries will be required for any large-scale energy storage applications. Battery systems more expensive than lead-acid will not be usable. Various secondary battery systems are reviewed in later sections of this report. Some of these secondary batteries are not suitable from first considerations. Thus, batteries like nickel-cadmium, which are lighter and more compact than lead-acid, are not practical, since they are a factor of two more costly.

The long-lived, sintered nickel electrode presently costs about \$18/kwh for the active material and an additional \$18/kwh for the sintered support. Any system using modified nickel-cadmium battery technology, such as nickel-iron, nickel-zinc and nickel-hydrogen, will be correspondingly non-competitive for large-scale energy storage.

The criterion of watt-hours per pound, which is significant in advanced batteries for mobile or space power, is not a critical item for stationary systems. The weight is only important in that it relates to amounts of active material and associated hardware, which, in turn, relate to cost. More important criteria are volume energy density and floor space or land area, as it relates to the final installed system.

Among the possible contenders for advanced energy storage battery systems are:

- Advanced lead-acid
- Zinc-air
- Alkali metal/metal sulfide
- Zinc-chlorine
- Redox.

These systems are undergoing intensive research and development now and the technical results are encouraging.

These advanced battery systems use highly energetic, intrinsically low-cost active materials for couples (though purity requirements may add to the costs). These systems use liquid or soluble reactants at the electrodes, which should lead to long life systems. However, the reactants are highly corrosive and some systems require high temperatures for operation. The containment of the highly reactive electrochemical reactants requires special materials and complex engineering systems. The final form of these systems will greatly depend upon the solutions to technical problems unearthed in the research and development work.

Cost projections for these systems are highly questionable. They are based upon present design concepts which use materials that have not been fully identified nor completely specified, let alone manufactured in quantity. They all depend upon costs decreasing with production. Although experience curve effects are generally encountered in manufacturing, the extent of this learning curve-cost reduction is not fully defined.

For example, laboratory scale single cell lithium/metal sulfide cells have a materials cost of \$2130/kwh. These cells produced on a pilot plant scale are projected to cost \$130/kwh for materials and, when manufactured on about a five MWH/day level, to have a materials cost of \$16.30 (4,5). Other system projections have similar cost reduction slopes. It appears that the projected costs are conveniently close to those quoted as targets for load-leveling systems. In general, the projected costs of various advanced systems appear to be low and probably reflect the optimism and immaturity of the technology.

There is no rational basis for rejecting (or accepting) the various published cost projections, assuming that each considered the essential parameters. They are a matter of judgment. A better feel for the state of advanced batteries, both their technology and costs, could possibly be obtained by visits to the various laboratories now studying these batteries. The purpose would be to obtain a "hands-on" feel for the systems and an in-depth, face-to-face discussion with the investigators and cost estimators.

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3. Gallwitz, W. "Lead-Acid Battery in Peak Power Demands", Final Report, May 1975-November 1975, ILZRO Project LE 239.
4. Yao, N. P. and Birk, J. Proceedings of the 10th Intersociety Energy Conversion Engineering Conference, IEEE, 1975.
5. Ivins, R., et al. "Design of Lithium/Sulfur Batteries for Load-leveling on Utility Networks", IEEE Symposium, April 8, 1975, Charlotte, North Carolina.

## 2. ELECTROCHEMICAL CANDIDATE SYSTEMS FOR BULK ENERGY STORAGE

There are a large number of possible secondary batteries. Some have properties which are suitable for energy storage systems, others not. A summary of the performance and life data for secondary batteries, as of 1975 is given in Table 2-1 (84). This table highlights the major features of the reported data on batteries given in Tables 2-4 to 2-16. A figure-of-merit can be developed for battery systems, using the rating criteria shown in Table 2-2. Application of this rating system to available secondary batteries is summarized in Table 2-3. The attractive candidate systems are:

- Lead-acid
- Zinc-halogen
- Metal-air
- Alkali metal sulfides
- Redox

Table 2-1

## Summary of Performance and Life Data for Selected Battery Systems

Battery System <sup>(a)</sup>	Open Circuit Voltage, V	Average Operating Voltage, V	Maximum Reported Ahr Capacity	Maximum Reported Power Level	Operating Temperature Range, °C	Typical Cycle Life, Cycles	Depth of Discharge, percent	Reported Ahr Efficiency percent	Reported Whr Efficiency percent
PbO <sub>2</sub> /Pb	2.09	1.70	5000	2.5 kw	0 - 100	≤2000	50	83 - 91	68 - 75
NiOOH/Cd	1.29	1.10	1245	1 kw	0 - 100	≤5000	50	70 - 85	60 - 75
NiOOH/Fe	1.37	1.20	750	--	0 - 100	≤3000	80	80	60
NiOOH/Zn	1.71	≥1.30	140	--	0 - 100	1200	90	~ 85	~ 70
NiOOH/H <sub>2</sub>	1.36	1.25	55	--	0 - 100	≤8000	≥50	~ 95	--
AgO/Cd	1.40	1.10	--	--	0 - 100	2500	45	90 - 95	70 - 75
Ag <sub>2</sub> O/Pb	1.60	1.50	300	1 kw	0 - 100	300	45	90 - 95	70 - 75
Ag <sub>2</sub> O/Zn	--	0.90	--	--	0 - 100	20	--	--	--
Ag <sub>2</sub> O/H <sub>2</sub>	1.50	1.10	500	--	0 - 100	1000	"deep"	--	--
Zn/Cl <sub>2</sub>	1.80	--	--	20 kw	0 - 100	>150	50	~ 95	~ 80
Zn/Cl <sub>2</sub> (H <sub>2</sub> O)	2.12	≥1.93	30,000	12.5 kw	0 - 100	(b)	≤100	--	--
Zn/Br <sub>2</sub>	1.80	--	--	--	0 - 100	poor	--	--	--
Na/(Me)Cl <sup>-</sup>	(≤4.00)	~3.00	5	1 kw	150 - 240	72	"deep"	--	87
Li(Al)/(Me)Cl <sub>2</sub>	3.46	--	30	--	400 - 680	200	≥50	--	--
Zn/O <sub>2</sub>	1.65	1.30	25	27 kw	0 - 100	200	50	~ 70	--
Na/O <sub>2</sub>	2.60	--	--	15 kw	100 - 250	--	--	--	--
Fe/O <sub>2</sub>	1.28	--	--	--	0 - 100	--	--	--	--
Cd/O <sub>2</sub>	1.21	≤0.85	12	--	0 - 100	≤500	"deep"	--	--
Na/S	2.08	1.84	700	1 kw	285 - 400	≥100	50	≤100	≤90
Li/S	2.25	--	--	30 kw	300 - 450	≥100	--	80 - 100	80 - 85
Li/Se	2.10	--	--	--	350 - 400	>100	--	--	--
Li/Te	≥1.75	≥1.55	--	≤170 kw	400 - 470	>200	--	--	--
Li-Al/FeS <sub>2</sub>	<1.77	≤1.50	150	≤118 w	300 - 400	250	--	80	≤74
Redox	0.74 - 1.74	--	0.38	--	0 - 100	(b)	90	≤99	70

(a) Alloying additions or other principal components are sometimes used. These are given in parenthesis.

(b) Indefinite cycle life with proper maintenance of solution compositions.

Note: Me represents a metal.

Table 2-2

Rating Criteria for Establishing a  
Figure of Merit for Selected Battery Systems

Parameter	Value of 1 Assigned	Value of 2 Assigned
(a) Average operating voltage, V	≤1.00	≥1.00
Maximum Ahr capacity reported, Ahr	≤100	≥100
Operating temperature, °C (°F)	≥100(212)	≤100(212)
Cycle life, cycles	≤1000	≥1000
Depth of discharge, percent	≤50	≥50
Whr Efficiency, percent	≤75	≥75
Energy density, Whr/Kg (Whr/lb)	≤55(≤25)	≥55(≥25)
Power density, W/Kg(W/lb)	≤55(≤25)	≥55(≥25)
(b) Cost, \$/kWhr	≥50	≤50

Maximum possible rating = 32

Minimum possible rating = 8



Table 2-3

Determination of the Figure of Merit for Selected Battery Systems

Battery Type <sup>(a)</sup>	Average Operating Voltage	Maximum Ahr Capacity	Operating Temperature	Cycle Life	Depth of Discharge	Whr Efficiency	Energy Density	Power Density	Total	Cost	Figure of Merit
PbO <sub>2</sub> /Pb	2	2	2	2	1	1	1	1	12	(2)	(24)
NiOOH/Cd	2	2	2	2	1	1	1	1	12	1	12
NiOOH/Fe	2	2	2	2	2	1	1	(2)	(14)	1	(14)
NiOOH/Zn	2	2	2	2	2	1	2	2	15	1	15
NiOOH/H <sub>2</sub>	2	1	2	2	2	(2)	2	2	(15)	1	(15)
AgO/Cd	2	1	2	2	1	1	(1)	(2)	(12)	1	(12)
AgO/Zn	2	2	2	1	1	1	2	2	13	1	13
Ag <sub>2</sub> O/Pb	1	1	2	1	1	(1)	1	(1)	(9)	(1)	(9)
Ag <sub>2</sub> O/H <sub>2</sub>	2	2	2	2	2	(1)	2	2	(15)	1	(15)
Zn/Cl <sub>2</sub>	2	2	2	1	2	2	(2)	(2)	(15)	2	(30)
Zn/Cl <sub>2</sub> ·6H <sub>2</sub> O	2	2	2	2	2	(2)	2	1	(15)	(2)	(30)
Zn/Br <sub>2</sub>	(2)	1	2	1	(2)	(1)	1	2	(12)	2	(24)
Na/(Me)Cl <sup>-</sup>	2	1	1	1	2	2	2	1	12	(2)	(24)
Li(Al)/(Me)Cl <sub>2</sub>	2	1	1	1	2	(1)	(2)	2	(12)	1	(12)
Zn/O <sub>2</sub>	2	1	2	1	2	1	2	1	12	2	24
Na/O <sub>2</sub>	(2)	1	1	1	1	1	(2)	(2)	(11)	(2)	(22)
Fe/O <sub>2</sub>	(2)	1	2	1	1	1	2	(2)	(12)	(2)	(24)
Cd/O <sub>2</sub>	1	1	2	1	2	1	2	(2)	(12)	(2)	(24)
Na/S	2	2	1	1	2	2	2	1	13	2	26
Li/S	(2)	1	1	1	(2)	2	2	2	(13)	2	(26)
Li/Se	(2)	1	1	1	(2)	(1)	2	(2)	(12)	(2)	(24)
Li/Te	2	1	1	1	(2)	(1)	2	2	(12)	(2)	(24)
Li-Al/FeS <sub>2</sub>	2	2	1	(1)	2	(1)	2	2;	(13)	2	(26)
Redox	(1)	1	2	2	2	1	(1)	(1)	(11)	(2)	(22)

(a) Alloying additions on these principal components are sometimes used. These are given in parentheses, Me represents a metal.

Table 2-4

Economic and Performance Data for Lead-Acid Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
1.(1966)	--	12	--	--	--	--	--	--
2.(1967)	70	8-18	--	--	1-20	--	--	--
3.(1967)	--	11	--	--	3	--	--	--
4.(1968)	11	16-20	1.5-2.0	--	--	--	--	--
5.(1971)	--	5-15	0.4-1.0	--	10	--	556	55
6.(1972)	--	10-18	--	--	--	--	--	--
7.(1973)**	--	35*	--	100*	--	--	500	--
8.(1973)	5000	--	--	--	--	--	--	56
9.(1973)	250	≥11	--	--	6	--	--	--
10.(1974)	--	≥17	--	--	--	≤1.00	--	--
11.(1974)	--	15	--	15	1	1.00	--	100
12.(1974)	--	16-18	--	25	--	--	--	20-50
13.(1974)	--	10	--	10	1	1.00	--	110
14.(1974)*	--	16-20	--	35*	10	--	--	--
15.(1974)	--	9-13	--	5-8	1	--	190-311	71-132
16.(1974)	--	17-23	--	--	5	--	--	--
17.(1974)	--	12	1.1	--	10	--	≥300	≥30
18.(1974)	--	--	--	--	--	--	--	20-140
Averages <sup>(b)</sup>	--	17	0.9	(15)	5-10	(1.00)	≥450	≥50

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* High rates of discharge only.

\*\* Load-leveling applications.

Table 2-5

Economic and Performance Data for Nickel Hydroxide-Cadmium Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
19. (1966)	--	9-14	0.7-1.3	--	--	--	--	--
2. (1967)	--	18-20	--	--	--	--	--	--
3. (1967)	--	10-15	0.7-1.0	--	3	--	--	--
20. (1968)	--	10-12	0.9-1.1	--	--	--	--	--
21. (1969)	--	15	--	70	--	--	--	400
22. (1969)	--	14	--	--	--	--	--	--
23. (1971)	--	13	0.7	--	--	--	--	--
24. (1971)	20	25	1.9	--	--	--	--	--
5. (1971)	--	12-20	0.9-1.0	--	--	--	--	320
6. (1972)	--	≤25	--	--	5	--	--	--
7. (1973) *	--	15	--	300	--	--	1500	--
13. (1974)	--	14	--	14	1	5.00	--	360
10. (1974)	--	17-20	--	--	--	--	--	--
14. (1974)	--	18	--	18	1	--	--	--
Averages <sup>(b)</sup>	--	(16)	(1.1)	(100)	--	(5.00)	1500	(360)

(a) References given at the end of this section.

(b) For typical load, leveling duty cycles, e.g., 5-15 hours discharge period.

\* Load leveling applications.

Table 2-6

Economic and Performance Data for Nickel Hydroxide-Iron Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
1. (1966)	--	11	--	--	--	--	--	--
3. (1967)	--	13	--	--	3	--	--	--
20. (1968)	--	12-13	0.9-1.2	--	--	--	--	--
22. (1969)	--	11	--	--	--	--	--	--
5. (1971)	--	7-10	0.7-1.0	--	--	--	--	--
25. (1974)	--	22	--	40	--	2.20	--	--
10. (1974)	--	17	--	--	--	--	--	--
12. (1974)*	--	20-30	--	60	--	--	--	20-30
11. (1974)	--	10	--	10	1	2.00	--	--
14. (1974)	--	20	--	20	1	--	--	--
Averages <sup>(b)</sup>	--	(15)	(1.0)	(32)	--	(2.10)	--	(20-30)

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Thought to be achievable in 1976.

Table 2-7

Economic and Performance Data for Nickel-Hydroxide-Zinc Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
26. (1967)	2.5	16	--	--	2	--	--	--
27. (1970)	5-25	≥20	1.5	100	--	--	--	--
28. (1971)	--	40-50	--	--	--	--	--	--
29. (1971)	--	15-30	--	--	--	--	--	--
30. (1972)	68-83	16-24	--	25-150	≤1	--	--	--
6. (1972)	--	≥30	--	--	--	--	--	--
31. (1973)	100	32-35	--	35-40	5	--	--	≥65
10. (1974)	140	20-23	--	--	0.25-5	>2.00	--	--
12. (1974)*	--	30-40	--	75	--	--	--	20-25
32. (1974)	--	20-25	--	>100	--	--	--	--
13. (1974)	--	25	--	25	1	4.00	--	150
33. (1974)	4-8	≤18	--	--	1	--	--	--
14. (1974)	--	25-30	--	25-30	1	--	--	--
Averages <sup>(b)</sup>	--	(25)	(1.5)	≥35	--	(>2.00)	--	≥65

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Projected to be available in 1977.

Table 2-8

Economic and Performance Data for Nickel-Hydroxide-Hydrogen Batteries

Reference, and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
34. (1972)	--	25-42	0.8	--	--	--	--	--
35. (1972)*	50	40	--	--	--	--	--	--
36. (1973)	5-50	25-30	1.0	50-100	0.2-15	--	--	1500
37. (1973)**	500	15-45	--	--	--	--	--	1500
38. (1974)	50	30	--	--	--	--	--	--
39. (1974)	20-55	27	≤ 0.8	--	--	--	--	--
58. (1975)	1.5-50	28	--	(>135)	0.2-2	--	--	--
Averages <sup>(b)</sup>	--	30	≥ 0.8	75	--	--	--	1500

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Computer prediction based upon experimental data.

\*\* Extrapolated from single cell data.

Table 2-9

Economic and Performance Data for Silver Oxide-Cadmium and Silver Oxide-Lead Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>A. Silver Oxide-Cadmium</u>								
40. (1965)	--	12-40	0.7-3.0	--	--	--	--	--
19. (1966)	--	8-19	0.4-2.6	--	--	--	--	--
3. (1967)	--	25	--	--	3	--	--	--
20. (1968)	--	15-35	1.8-2.9	--	--	--	--	--
22. (1969)	--	30	--	--	--	--	--	--
27. (1970)	--	30	--	--	--	--	--	--
5. (1971)	--	16-25	0.4-2.9	--	--	--	--	415
10. (1974)	--	23	--	--	--	--	--	--
Averages <sup>(b)</sup>	--	(24)	(2.1)	--	--	--	--	(415)
<u>B. Silver Oxide-Lead</u>								
45. (1965)	--	17	2.4	--	--	--	--	--

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

Table 2-10

Economic and Performance Data for Silver Oxide-Zinc Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
41. (1960)	--	70	--	--	30-40	--	--	--
40. (1965)	--	26-60	1.4-4.0	--	--	--	--	--
42. (1965)	--	24-57	--	--	--	--	--	--
1. (1966)	--	50	--	--	--	--	--	--
19. (1966)	--	25-40	1.8-3.0	--	--	--	--	--
3. (1967)	--	41-52	--	--	3	--	--	--
43. (1967)	21-165	24-57	2.1-3.4	2-185	16.5	--	--	--
2. (1967)	--	40-50	--	--	--	--	--	--
20. (1968)	--	30-80	2.0-4.5	--	--	--	--	--
22. (1969)	--	30	--	--	--	--	--	--
21. (1969)	--	45	--	75	--	--	--	800
44. (1970)	--	41	--	--	0.17	--	--	--
5. (1971)	--	25-65	0.7-3.5	--	--	--	--	470
37. (1973)	500	--	--	--	--	--	--	740
8. (1973)	5000	--	--	--	--	--	--	115-245
31. (1973)	100	50-60	--	--	--	--	--	>>108
10. (1974)	--	55	--	--	--	--	--	--
14. (1974)	--	50	--	50	--	30	--	--
11. (1974)	--	40	--	40	1	20	--	>360
Averages <sup>(b)</sup>	--	45	2.7	( 65)	--	(25)	--	(>440)

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.



Table 2-11

Economic and Performance Data for Silver Oxide-Hydrogen Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
34. (1972)	0.5	35-60	0.8	---	---	---	---	---
37. (1973)	500	30-95	---	<1500	---	---	---	840
38. (1974)	---	41-50	---	---	---	---	---	---
46. (1974)	20	45-60	0.8	---	---	---	---	---
Averages <sup>(b)</sup>	---	(50)	(0.8)	(<1500)	---	---	---	(840)

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge time.

Table 2-12

Economic and Performance Data for Metal-Halogen or Halide Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>A. Zinc-Chlorine</u>								
47. (1974)	---	65	3.6	---	---	---	---	32
11. (1974)	---	50	---	50	1	>1.00	---	>15
14. (1974)	---	60-70	---	60-70	1	---	---	---
32. (1974)	---	60-80	---	<100	---	---	---	---
48. (1974)	(20kw)	50-74	---	10(40-60*)	---	---	---	---
Averages <sup>(b)</sup>	---	(62)	(3.6)	(56)	---	(>1.00)	---	(>15)
<u>B. Zinc-Chlorine Hydrate</u>								
49. (1973)	(3kw)	30	---	9	20	---	---	---
49. (1973)	(3kw)	20	---	(27*)	2.5	---	---	---
50. (1974)	(12.5kw)	61	2.9	18(27-71*)	4	---	---	10-20**
Averages <sup>(b)</sup>	---	50	2.9	14	---	---	---	(10-20**)
<u>C. Zinc-Bromine</u>								
6. (1972)	---	22	---	---	2	---	---	---
32. (1974)	---	20	---	40-50	---	---	---	---
Averages <sup>(b)</sup>	---	(21)	---	(45)	---	---	---	---

Table 2-12 (Continued)

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>D. Sodium-Chloraluminate</u>								
51. (1974)***	(5kw)	45	~2.7	--	10	---	---	---
<u>E. Lithium-Chlorine</u>								
52. (1967)	---	12-36	---	100	---	---	---	---
22. (1969)	---	125-250	---	200	---	5-7	---	---
5. (1971)***	---	120-170	---	---	---	---	---	---
28. (1971)	---	100-300	---	---	---	---	---	---
53. (1971) <sup>+</sup>	---	20-25	≥5	< 200	---	---	---	---
6. (1972)	---	38	---	---	---	---	---	---
54. (1973)	---	250	---	---	---	---	---	---
48. (1974)	---	37	---	---	---	---	---	---
32. (1974)***	---	≤50	---	≥100	---	---	---	---
14. (1974)	---	≥70	---	≥100	---	---	---	---
10. (1974)	---	68	---	---	---	---	---	---
55. (1974)	---	160	---	≤280	---	---	---	---
Averages <sup>(b)</sup>	---	(~85)	(≥5)	(≥100)	---	(6)	---	---

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Intermittent, fast-rate use.

\*\* Predicted large volume application: cost for small volume usage ~ 200\$/kwhr.

\*\*\* Extrapolated from single cell data.

+ Li-Al alloy anode; Te or Se chloride cathode, eg. TeCl<sub>4</sub>

Table 2-13

Economic and Performance Data for Metal-Oxygen or Air Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>A. Zinc-Oxygen/Air</u>								
40. (1964)	---	53	---	---	---	---	---	---
56. (1966)*	---	120	---	---	8	---	---	---
21. (1969)**	---	80	---	45	---	---	---	---
22. (1969)	---	50-60	---	30-35	---	1.50-3.30	---	---
57. (1970)***	(3kw)	30-41	---	11	5-10	---	---	---
28. (1971)	---	60-100	---	30-40	---	---	---	---
29. (1971)	---	35-40	---	---	5	---	---	---
59. (1972)*	25	60	2.7	---	5	---	---	---
60. (1972)**	(1kw)	30	---	20	---	---	---	---
34. (1972)	---	50-100	1.8	---	---	---	---	---
61. (1974)* <sup>+</sup>	20	60	---	---	3	---	---	---
60. (1974)*	(20kw)	27	---	28	---	---	---	---
10. (1974)	---	41	---	10	50-100 <sup>++</sup>	---	100	---
10. (1974)**	(21kw)	42	---	31	---	---	---	---
11. (1974)	---	30	---	30	1	<1.00	---	<36
32. (1974)	---	40-50	---	20-20	---	---	---	---
Averages <sup>(b)</sup>	---	59	2.3	>10	---	(≤3.30)	100	(<36)

Table 2-13 (Continued)

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>B. Sodium-Oxygen/Air</u>								
22. (1969)*	--	100-150	--	40-50	--	1.50-2.00	--	--
28. (1971)	--	160-215	--	25-35	--	--	--	--
81. (1972)	(1kw)	160-300	--	30-55	--	--	--	--
Averages <sup>(b)</sup>	--	(180)	--	(40)	--	(1.75)	--	--
<u>C. Iron-Oxygen</u>								
10. (1974)	--	23-50	--	--	--	--	--	--
<u>D. Cadmium-Oxygen/Air</u>								
62. (1968)*	--	23-30	--	--	2-24	--	--	--
63. (1968)	12	43-51	3.5-4.0	--	2-10	--	--	--
58. (1971)	--	40-50	2.3-4.0	--	2-10	--	--	--
34. (1972)*	--	25-43	1.2	--	--	--	--	--
10. (1974)	--	50	--	--	--	--	--	--
Averages <sup>(b)</sup>	--	39	3.5	--	--	--	--	--

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Oxygen as cathode reactant;

\*\* Mechanically rechargeable zinc electrodes.

\*\*\* Circulating electrolyte system.

+ Amalgamated silver cathode.

Table 2-14

## Economic and Performance Data for Sodium-Sulfur Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
3. (1967)	--	136	--	--	--	--	--	--
22. (1969)	--	150	--	150	--	--	--	--
64. (1970)*	700	190	--	--	--	--	--	--
5. (1971)	--	80-120	--	--	--	--	--	--
65. (1972)	--	43	0.4	95	--	--	--	--
66. (1972)**	(10kw)	100	1.45	--	12	--	133	>10
67. (1972)***	1.6	≤60	--	--	1	--	--	--
68. (1972) <sup>+</sup>	20	35	--	70-110	2	--	--	--
68. (1972)	20	3.5	--	7-11	2	--	--	--
69. (1972)	<40	<100	--	<100	--	--	--	--
11. (1974)	--	68	--	68	1	>1.00	--	>10
48. (1974)	(0.35kw)	<42	--	<95	--	--	--	--
32. (1974)*	--	≤100	--	≤100	--	--	--	--
14. (1974)*	--	>100	--	>100	--	--	--	--
10. (1974)	(1kw)	45-114	--	--	--	--	--	--
70. (1974)	--	105	--	--	--	--	--	--
71. (1974)*	17	≥60	7.5	--	8	--	--	--
72. (1974)*	17	<93	7.5	<12	8	--	--	12-18
Averages <sup>(b)</sup>	--	≤87	>5.5	<12	--	(>1.00)	133	>10

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Extrapolated from single cell data.

\*\* Load leveling application.

\*\*\* Based on active materials only.

+ Not including thermal insulation and packaging.

Table 2-15

Economic and Performance Data for Lithium-Chalcogen Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$/kw	\$/kwhr
<u>A. Lithium-Sulfur</u>								
22. (1969)	---	150	---	300	---	---	---	---
73. (1970)*	(>110kw)	<188	---	<130	---	2.56	---	---
11. (1974)	---	50	---	50	---	3.00	---	30
48. (1974)	---	100	---	50-70	---	---	---	---
32. (1974)*	---	≥100	---	≥100	---	---	---	---
14. (1974)*	---	>100	---	>100	---	---	---	---
10. (1974)*	---	150	---	---	---	---	---	---
Averages <sup>(b)</sup>	---	(120)	---	(≥123)	---	(2.78)	---	(30)
<u>B. Lithium-Selenium</u>								
10. (1974)	---	136	---	---	---	---	---	---
<u>C. Lithium-Tellurium</u>								
28. (1971)+	---	90	2-10	140	---	---	---	---
10. (1974)*	---	114	---	---	---	---	---	---
Averages <sup>(b)</sup>	---	(102)	(6)	(140)	---	---	---	---

Table 2-15 (Continued)

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density,		Power Density, w/lb	Discharge Rate, hr	Cost		
		whr/lb	whr/in <sup>3</sup>			\$/lb	\$kw	\$/kwhr
<u>D. Lithium-Iron Sulfide</u>								
74. (1974)**†	6000	59	--	≤ 54	10	--	--	50-100
75. (1974)*	(40Mw)	52-77	6.7-9.2	--	8	--	--	>10
76. (1974)*†	150	≥ 68	--	--	--	--	--	--
77. (1974)**†	(1Mw)	76	--	75-30	10	--	--	20
Averages <sup>(b)</sup>	--	66	8.0	<54	--	--	--	≥ 35

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Experimental single cell data, or extrapolations therefrom.

\*\* Design goals based on experimental data.

+ Lithium-aluminum alloy anode.



Table 2-16

Economic and Performance Data for Redox Batteries

Reference and Year <sup>(a)</sup>	Size amp-hr	Energy Density, whr/liter	Power Density, w/lb	Discharge Rate, hr	Cost		
					\$/lb	\$/kw	\$/kwhr
<u>A. Cr<sup>2</sup>/Cr<sup>3</sup>/Cr<sup>6</sup> System</u>							
16. (1974)	--	50	--	5	--	--	35-45
78. (1974)	--	46	--	--	--	--	--
79. (1974)*	(100Mw)	--	--	5	--	37	175
Averages <sup>(b)</sup>	--	48	--	5	--	(37)	(>>35)
<u>B. Fe/Cr System</u>							
78. (1974)	--	12	--	--	--	--	--
<u>C. Ti/Cr System</u>							
78. (1974)	--	11	--	--	--	--	--
<u>D. Ti/Fe System</u>							
80. (1974)	0.38	20	--	1.5	--	--	--
78. (1974)	--	4	--	--	--	--	--
83. (1973)	(10Mw)	--	<6	8.5	--	185-287	--

(a) References given at the end of this section.

(b) For typical load leveling duty cycles, eg. 5-15 hours discharge period.

\* Design prediction based on experimental data.

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## 2.1 Lead-Acid Batteries

Lead-acid batteries have been in existence for over 100 years. During this time period, improvements have been more evolutionary than revolutionary. Today there are three basic types of lead-acid battery available, (1) starting, lighting, and ignition (SLI) batteries for vehicles such as automobiles, (2) traction batteries for industrial and recreational vehicles such as golf carts, and fork-lift trucks, and (3) stationary batteries for emergency and standby power in public buildings and critical installations such as uninterruptible switching and automatic protective devices in power stations and substations. The storage capacity in each of the three application areas outlined above tends to increase in the order given. The requirements for a bulk energy storage battery are sufficiently different from the above that a fourth category will become necessary for classifying the types of lead-acid battery available in the future.

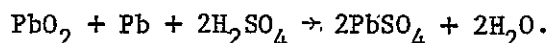
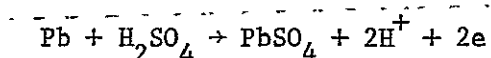
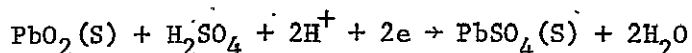
The manufacturing cost for conventional lead-acid batteries is relatively well known, and the manufacturing technology is well established. Data for lead-acid storage battery systems can be taken as a reference point for comparison with other storage battery systems for energy storage applications.

Although the performance and cost of state-of-the-art lead-acid batteries leaves much to be desired, the lead time for installing energy storage capacity is considered to be short. Of the battery systems, lead-acid batteries are probably the only type which could be installed before 1980, even if not optimized for energy storage applications.

For these reasons (as discussed in the introduction) EPRI, ERDA and ILZRO have sponsored a detailed design and cost analysis of special state-of-the-art lead-acid batteries by ESB, CTD and Gould. These analyses will serve as the general basis for the following discussion.

In the normal lead-acid battery, the positive electrode consists of specially-formulated electrochemically active lead dioxide, while the negative consists of porous metallic lead. Both the active materials are supported on lead or lead alloy grids (current collectors). All the positives in each cell are joined to a lead-alloy terminal post, similarly all the negatives are joined to another terminal post. Sulfuric acid electrolyte is used. A separator is used between each positive and negative electrode to prevent an electronic conduction path (short) forming between them, and also to achieve uniform, parallel spacing of the electrodes. The cells are connected in series to form a battery of the desired voltage, usually 6 or 12 volts, because each cell has a low drain voltage of about 2 volts. Battery cases traditionally were made from hard rubber or glass, but new materials such as synthetic rubbers and plastics, such as polypropylene, are becoming more popular.

The reactions in the lead-acid battery during discharge are in general:



The cell voltage is nominally 2 volts, but is a function of temperature, acid concentration and state of charge. The free energy of the reaction is greater than the enthalpy and the perfect battery would absorb heat on discharge. The thermal neutral voltage is less than the open circuit voltage. In practice, some heat is evolved, more on charge than discharge.

These characteristics for an ESB-designed lead-acid battery for load leveling are given in Tables 2.1-1, 2.1-2 and 2.1-3. Additional details on these and other characteristics of lead-acid batteries in general are given in Vinal's text, "Storage Batteries" (1).

Cooling systems will probably be required for the lead-acid energy storage batteries. The design studies provided for coolant loops in the batteries. Since there are acid concentration gradients produced during charge/discharge, air bubble stirring is provided to mix the electrolyte.

Table 2.1-1

Equilibrium Open Circuit Voltages and Corresponding  
Thermo-Neutral Voltages

Discharge Rate hrs.	Depth of Discharge %	Acid Concentration %	Equilibrium Open Circuit Voltage Volts	Thermo- Neutral Voltage Volts
-	0	35.6	2.110	2.033
1	45.8	30.4	2.068	1.995
2	56.0	28.6	2.054	1.980
3	61.9	27.6	2.046	1.971
4	65.6	27.0	2.042	1.966
5	69.0	26.4	2.036	1.962
6	72.5	25.8	2.032	1.956
7	77.3	25.0	2.026	1.951
10	80.0	24.6	2.024	1.947

Table 2.1-2

Evolution of Heat in VLL45 Cell and Temperature Rise on Discharge

Discharge Rate Hr	Discharge Capacity Ahr (80% Depth)	Mean Thermo- Neutral Voltage Volts	Mean Discharge Voltage Volts	(MTNW- MDV) Volts	Heat Evolved Whr	Temperature Rise (ΔT) °F
10	10,000	1.990	1.975	.015	150	1.1
7	9,464	1.992	1.942	.050	473	3.4
5	8,700	1.998	1.925	.073	635	4.6
3	7,800	2.002	1.873	.129	1006	7.3
1	5,720	2.014	1.685	.329	1882	13.7

$$\Delta T = \frac{(\text{Whr heat} \times 3.413 \text{ Btu/Whr})}{(2250 \text{ lbs} \times .209 \text{ Btu/lb } ^\circ\text{F})}$$

Table 2.1-3

Discharge Capacity vs Operating Temperature VLL-45 Cells

Discharge Temperature °F	Ratio of Capacity at <u>1 hr</u>	Ratio of Capacity at <u>3 hr</u>	Ratio of Capacity at <u>5 hr</u>	Ratio of Capacity at <u>6 hr</u>	Ratio of Capacity at <u>10 hr</u>
60	.90	.92	.94	.94	.95
70	.95	.96	.97	.97	.98
80	1.00	1.00	1.00	1.00	1.00
90	1.03	1.03	1.02	1.02	1.02
100	1.07	1.04	1.03	1.04	1.03
110	1.08	1.06	1.05	1.05	1.04
120	1.10	1.07	1.06	1.06	1.04
130	1.13	1.09	1.07	1.07	1.05

Final Cell Volts: (volts per cell at cell terminals)

80	1.46	1.61	1.65	1.66	1.69
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Detailed discussions of the charge/discharge characteristics of a load leveling lead-acid battery, using the ESB design as an example, are given in the section on battery charging.

The question of cycle life of a battery enters greatly into the construction considerations and, therefore, battery weight and cost. If, for example, a lead-acid battery is shallowly discharged, i.e., the active materials are only slightly used, the cycle life is large. Deep depths of discharge shorten life. The general considerations are shown in Figure 2.1-1. The principle is applicable to batteries in general. Thus, to have an assurance of 10,000 ampere hours of capacity at design depth of discharge, ESB selected a 12,500 ampere hour cell and C&D a 14,000 ampere hour cell. The non-usable active material factor adds to the cost, weight and volume.

The cycle life depends greatly on the bonding and retention of active materials on the grids and the corrosion resistance of the grids. This requires the use of special alloys and construction techniques. The distribution break-down of the components of the ESB battery electrodes are given in Table 2.1-4. The requirements of lead for support of active material and current collection are 44% of the total lead weight. About 40% of the lead in the cell is effectively used for energy storage.

Lead-acid batteries have routinely demonstrated 1000-2000 cycles for industrial batteries and, in a naval test, tubular plate grid batteries were cycled over 3400 times at a 6 hour rate over an 11 year period (2). These special batteries cost in excess of \$100/KWH (3).

This is an area for improvement in cost and weight of lead acid batteries, but the possibilities of success are low, based on the historical evolution of these batteries and field experience of necessary construction for cycle life.

It should be noted, however, that reduction of the amount of lead weight would not change the volume much and would not reduce the acid volume. The case and separator would remain nearly the same.

The manufacturing costs for ESB cells are given in Table 2.1-5. Again, there is not much room for improvement. The delivered cost of this battery power system is given in Table 2.1-6.

C&D arrived at similar costs without reporting as detailed an analysis. Gould had lower costs, but a rather vague description of battery assembly in the field, a questionable area. The projected life was seven years rather than ten.

A summary of the lead-acid battery energy storage system parameters from the detailed analysis was given in Tables 1.1-2 and 1.1-3. These parameters were for state-of-the-art batteries to be used in long cycle life systems. Significant improvements in these classical design batteries is unlikely.

While there have been indications of lead-acid batteries with double the WH/lb (4), the cycle life is only a few hundred cycles.

Figure 2.1-1

Relationship Between Depth of Discharge and  
Cycle Life for Lead-Acid Batteries

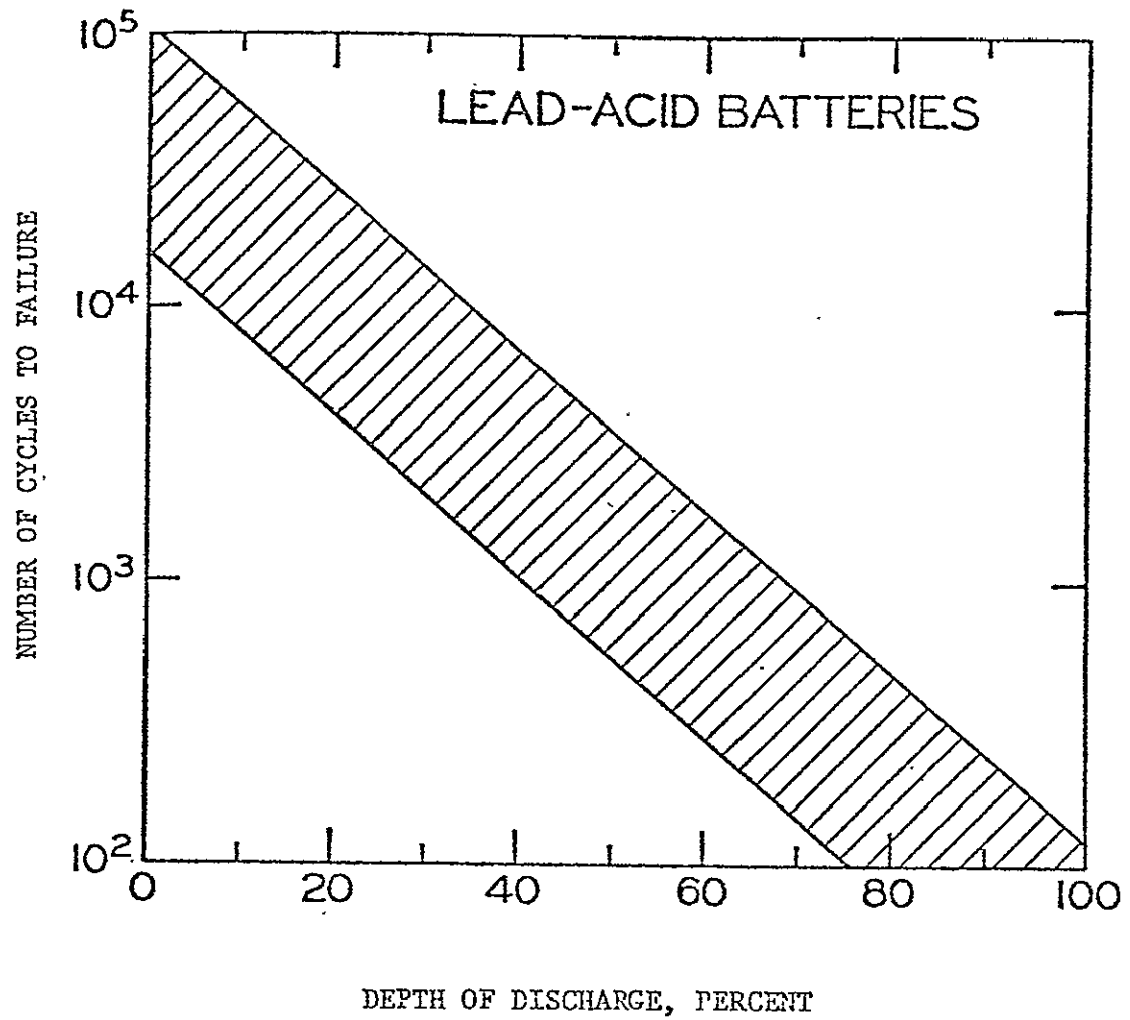


Table 2.1-4

Grid and Active Material Cost

Estimates for the VLL-45

Item	10MW, 50 MWhr Battery, 3072 Cells		10 MW, 100 MWhr Battery, 5250 Cells	
	lbs/ KWhr	\$/KWhr	lbs/KWhr	\$/KWhr
Positive Grid: Pb	22.2	4.44	18.8	3.76
Sb	1.4	2.80	1.2	2.40
Positive Active Material	26.2	5.24	22.2	4.44
Negative Grid	13.4	2.68	11.4	2.28
Negative A.M.	26.0	5.20	22.0	4.40
Post and Term: Pb	3.7	.74	3.1	.62
Sb	0.2	.40	0.2	.40
Total	93.1	21.50	78.9	18.30

Lead at \$0.20 per lb., Antimony at \$2.00 per lb.

Based on 80% Depth of Discharge

Table 2.1-5

Manufacturing Cost Estimates for the  
VLL-45 Cell Produced at 1000 MWhr per Year

Lead at \$0.20 per lb., Antimony at \$2.00 per lb.

Based on 80% Depth of Discharge

Item	10 MW, 50 MWhr Battery, 3072 Cells \$/KWH	10 MW, 100 MWhr Battery, 5250 Cells \$/KWH	Notes
Grids and Active Mat'ls	\$21.50	\$18.30	
Separators	3.07	2.60	
Jar and Cover	11.01	8.81	1
Copper	1.23	1.00	
Other Materials	9.78	8.31	
Total Materials	\$46.59	\$39.02	
Direct Labor	6.39	5.42	2
Overhead	12.55	10.66	3
Total Direct Costs	65.53	55.10	
Total Direct Costs (Revised jar)	57.65	48.79	1

Note 1: A jar concept is in hand which will still result in re-usable jars and permit a reduction of jar and cover cost by \$7.88 and \$6.31 respectively.

Note 2: Direct labor costs are based on the indication production rate and a production facility as discussed later.

Note 3: Overhead rate can vary markedly depending on rate, commitments and investment.

Table 2.1-6

Battery System Costs per Kilowatt-Hour of Energy  
Delivered at Rated 80% Depth of Discharge

Component	10MW, 50MWhr	10MW, 100MWhr
	Battery	Battery
	(3072 Cells)	(5250 Cells)
	<u>\$/KWhr</u>	<u>\$/KWhr</u>
Cell Costs	65.53	55.10
Intercell, buss connectors	2.15	1.83
Water Cooling System	5.68	5.20
Air Lift Pump System	.17	0.14
Electrical Monitoring System	1.20	0.91
Transportation	<u>2.20</u>	<u>2.10</u>
Estimated Grand Total:	<u>76.93</u>	<u>65.28</u>



There have been some vague reports (5) of improved plate and cell assemblies to give lighter weight. These reports are too skimpy to evaluate. Lead acid systems will probably never reach the target costs mentioned in the introduction.

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## 2.2 Zinc-Air Batteries

Zinc-air batteries are most attractive, on paper. A large number of organizations have investigated the zinc-air battery and nearly all have ceased their investigations (1-8). Only CGE in France is discussing an active program.

The basic chemistry of the zinc-air (oxygen) battery is shown in Figure 2.2-1. In discharge, oxygen (from air) is passed over or through the cathode and electrochemically converted to hydroxyl ions. At the anode, zinc metal is oxidized and the zinc ions react with the hydroxyl ions to produce zincate ions. In a subsequent chemical process, zincate ions may rearrange to produce zinc oxide solid and hydroxyl ions. The charge process is the reverse of the above.

The schematic of the cell process is shown in Figure 2.2-2 taken from a General Atomics paper (4).

The zinc-oxygen reaction has a relatively high potential and the energy density is high, both theoretically and practically, since oxygen (air) is generally not stored in the battery system. The cost of zinc is low and its utilization in the battery is high. Zinc can be conveniently plated on simple substrate electrodes, nickel, iron, copper, etc., in alkaline media. Since the operating temperature is low and alkali is used on the electrolyte, low cost construction materials can be used.

Millions of primary zinc-air cells have been made. They are the main battery used by the railroads and the Coast Guard for signal lighting. Attempts to make secondary zinc-air cells with stationary or static alkaline electrolytes have not been very successful.

Zinc dendrite formation and shape change of the zinc electrode due to concentration gradients in the electrolyte from gravity have limited the cycle life. Secondary zinc-air batteries with circulating electrolyte were studied extensively by General Atomics in the 60's (3-5). Poor zinc deposits and short life of reversed air electrodes stopped this phase of the work. An electrode structure and materials which could be used for both the production and consumption of oxygen was the principle problem.

The General Atomics work then shifted to a mechanically rechargeable system (2). In this approach, the steel anode substrates, when depleted of zinc, were removed from the battery, together with the electrolyte. Zinc was then plated on to the substrate anodes in a separate recharger, using the zinc oxide from the cells. The replated anodes were then returned to the battery system. This mechanically recharging approach was soon dropped and zinc-air work at General Atomic ceased.

General Motors (1) also worked on the mechanically rechargeable zinc-air system for electric vehicle batteries in the late 60's, but soon found it not viable for vehicles.

Figure 2.2-1

Zinc-Air Battery Chemistry

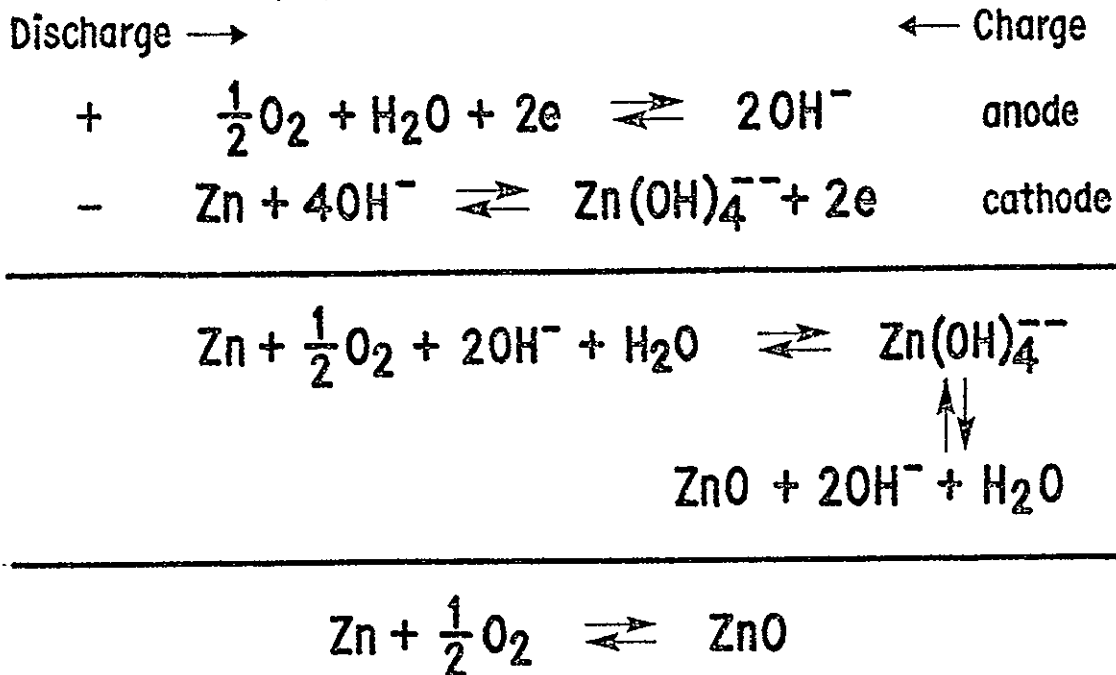
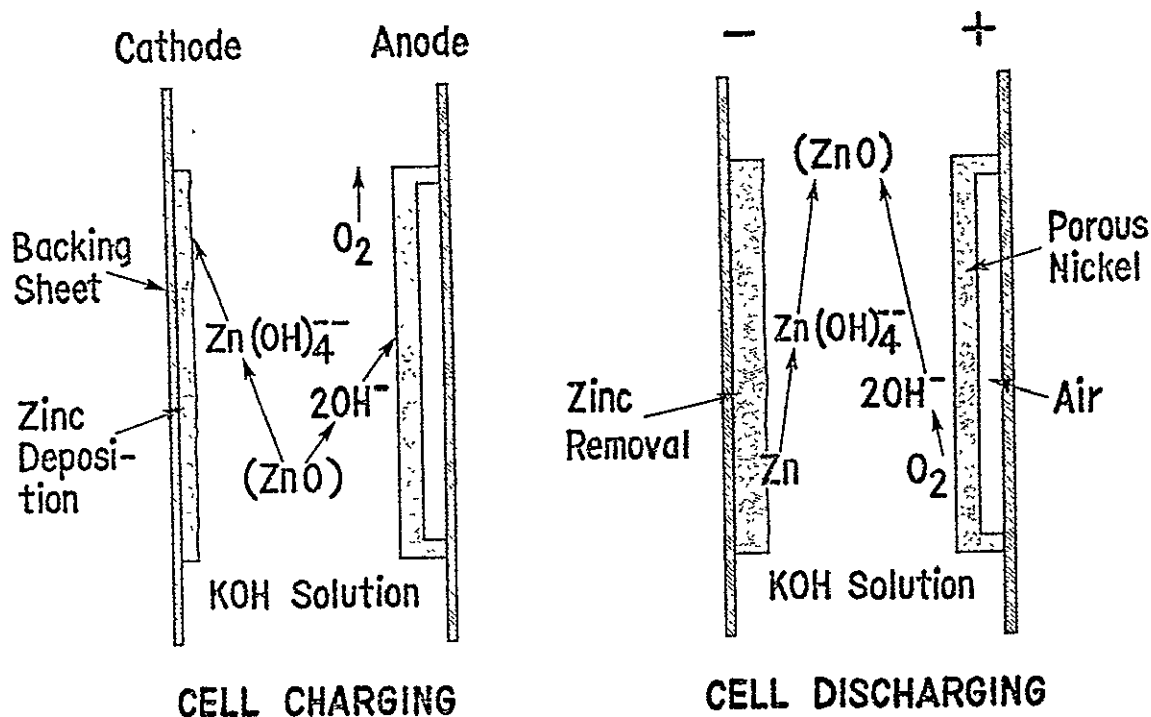


Figure 2.2-2

Zinc-Air Battery Cell Processes



Sony (6) in Japan worked on secondary zinc-air batteries which were "fueled" with zinc metal slurry in KOH solution. The system was complex and the power density was low. Work aimed at electric vehicles applications has stopped.

CGE (Compagnie Generale d' Electricite, Laboratoires de Marcoussis) has been working since 1972 on a secondary zinc-air system (7, 8). This system is illustrated schematically in Figure 2.2-3. In this system, a circulated KOH electrolyte containing zinc powder is flowed through tubular batteries or cells. The latter are connected electrically in series. A tubular cell is shown in Figure 2.2-4. The zinc is oxidized electrochemically by air flowing over a bank module of tube cells, shown in Figure 2.2-5. The zincate solution formed is returned to the reservoir. Colloid stabilizers in the electrolyte allow high concentration of zincate in the electrolyte before precipitation; nearly 5 moles per liter of 12 M KOH. The electrolyte circulating in the reservoir of the power system picks up a new load of zinc powder and passes through the cell again.

For recharging, another electrochemical unit is used. This is shown in Figure 2.2-3. There, the zincate ions in the electrolyte are converted to zinc powder. This powder is stored for the next discharge.

Different types electrodes are used for oxygen production and consumption, eliminating the previous problems of the dual purpose cathodes.

Thus, the discharge system is separate and distinct from the charge system. This means that the charger can be designed for its most efficient operating mode for the desired charge time and the discharger can be designed for its optimum discharge time. The amount of energy stored depends only on the allowable storage facilities and investment in zinc and KOH.

The voltage-current curve for the system is shown in Figure 2.2-6. The discharge curve at a constant current is nearly flat. Since the zinc and oxygen are constantly supplied, the only source of change in cell voltage is the small electrolyte resistance change due to zincate formation. The system can thus be discharged at constant power. The voltage of the system would drop only when the zinc supply was exhausted (but there would generally be a surplus), or when the air supply was reduced or stopped. Similarly, the charger could operate at constant power.

For energy storage systems, suitable arrangement of the charger and discharger sections would allow constant and equal power charge and discharge and greatly reduce the complexity of the power conditioner.

The operating life of the zinc-air system will primarily be determined by the life of the air cathode. CGE states 3000 hours of laboratory testing. Since the air cathode is used only on discharge, this is equivalent to 300 to 600 cycles in an energy storage scheme.

Figure 2.2-3

Schematic Diagram of Charge and Discharge of the CGE  
Circulating Zinc/Air Battery

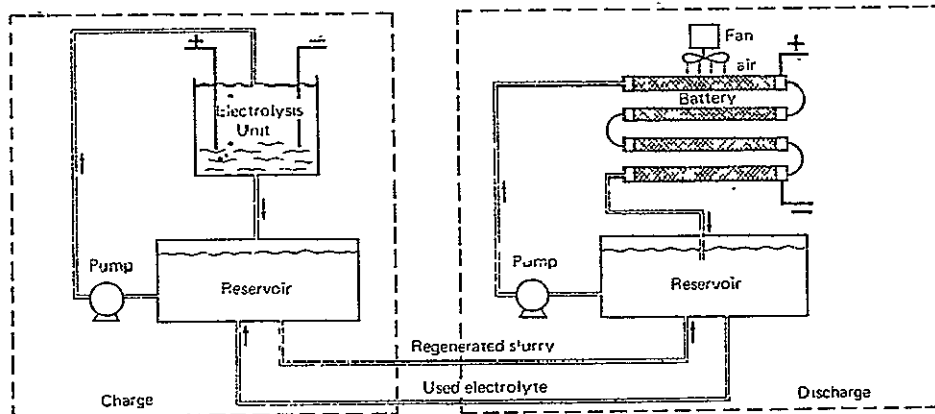


Figure 2.2-4

The CGE Circulating Zinc/Air Battery General Schematic  
View of a Tubular Cell and Cross-Section

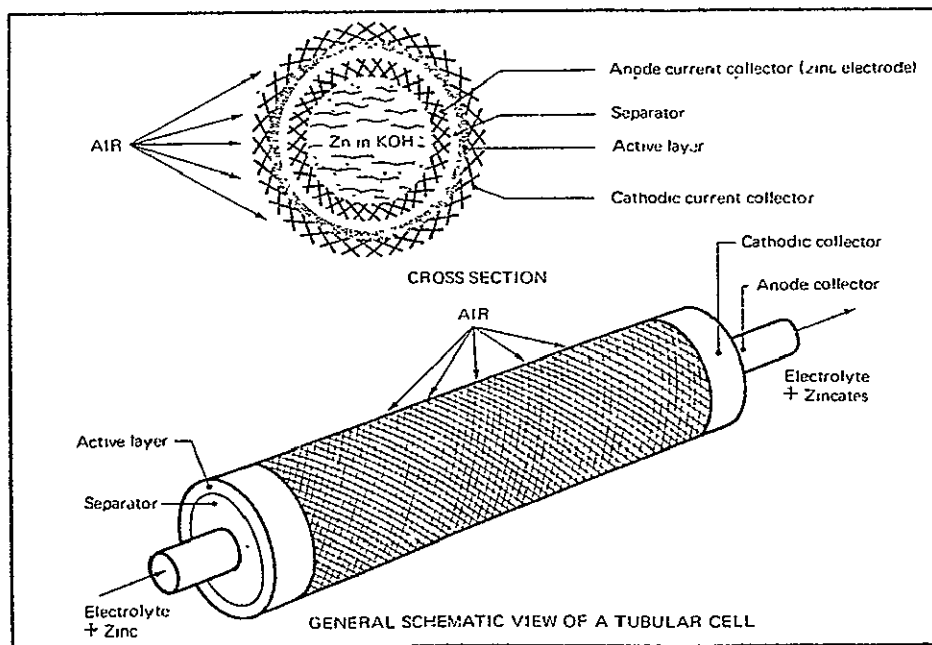


Figure 2.2-5

Battery Module

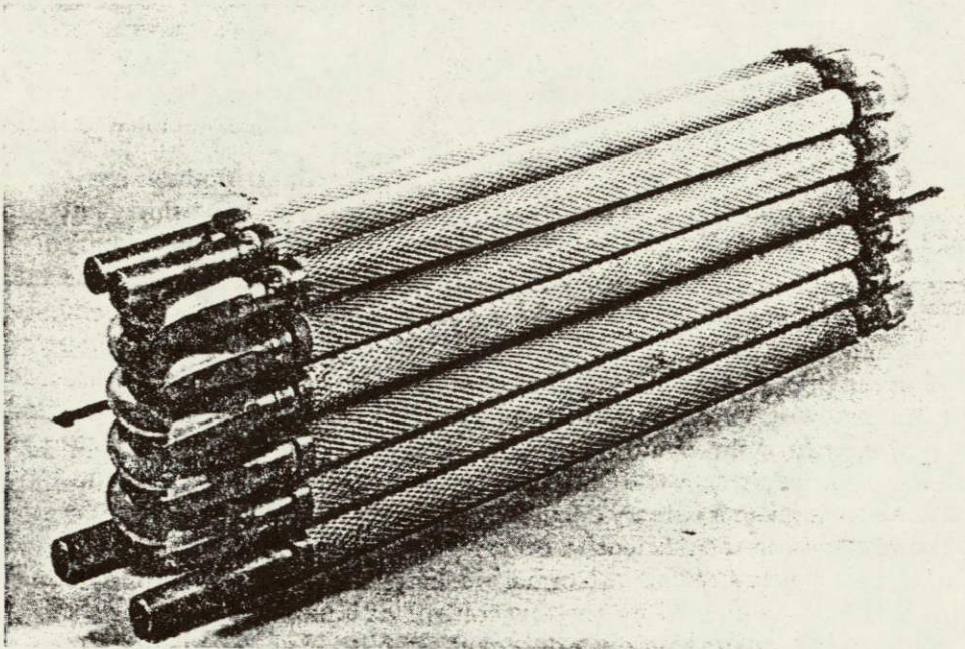
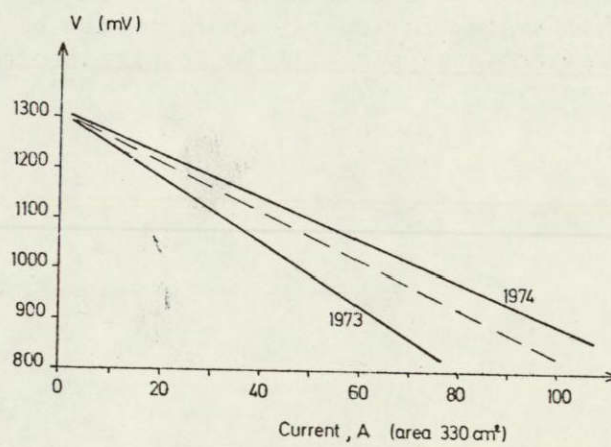


Figure 2.2-6

Current-voltage relationship for Tubes at 50°C, Showing  
Improvement in Performance



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OF POOR QUALITY



Because air is used at the alkaline electrolyte cathode, carbonation of the electrolyte from absorbed  $\text{CO}_2$  in the air is a problem. In the energy storage application, the air would have to be scrubbed or cleaned of  $\text{CO}_2$  and periodic replacement or regeneration of the KOH electrolyte would be required.

CGE has estimated that the cost of a vehicle type battery system, with a 3-hour discharge rate, would be \$35-45/KW. This includes the charger/discharger, power conditioning and pumps and motors to complete the system. In truck size vehicles, the installed cost of the zinc/air battery system is estimated to be 60% of a lead-acid battery system and the installed cost per KWH to be 30% of the equivalent lead-acid battery. The economics projected for a large-scale energy storage system could, therefore, be attractive.

The principle and deciding present disadvantage of the zinc-air system for energy storage is the turn-around efficiency. The present CGE battery operates at a nominal 1.2 volts on discharge at 80 ma/cm<sup>2</sup>, see Figure 2.2-6. A charging voltage of 2.4 volts is used to produce the zinc powder. These values, together with an estimate for faradaic losses and auxiliary power consumption, lead to a turn-around efficiency in the 40% range. This is unattractive for an energy storage system.

The major source of inefficiency is polarization of the oxygen electrode, both in charge and discharge. The zinc reaction has very little polarization. Improvements in the oxygen electrodes could markedly improve the turn-around efficiency. New oxygen evolution electrodes being developed for alkaline water electrolysis show polarizations of 100-200 mv rather than the 600-700 mv of those used in the CGE system. Oxygen cathodes being developed for alkaline fuel cells also show less polarization. Better oxygen electrodes could bring the turn-around efficiency into the 70% range.

Until such time as the turn-around efficiency can be significantly improved, the zinc-air system for energy storage will be marginally attractive. A total systems analysis will be required to determine the degree of improvement necessary.



### 2.3 Nickel-Zinc Batteries

Nickel-zinc batteries have received considerable attention in recent times as a possible electric vehicle battery (1-8). In this system, on discharge, nickel oxide is reduced and zinc is oxidized to zincate in an alkaline electrolyte. The open circuit voltage is approximately 1.9 v. and, under load, the discharge curve is relatively flat, as shown in Figure 2.3-1 (8). On charge, vented cells are charged at constant current to a voltage limit of less than two volts. The charging efficiency of the nickel electrode is 70-90%, depending on charge rate (the faster, the more efficient) and temperature. Thus, there is a return of 110 to 130% of the previous ampere hours removed. The inefficiency at the nickel electrode on charge results in evolution of oxygen. The zinc electrode is nearly 100% efficient on charge and, as a result, becomes fully charged before the nickel electrode. This results in a loss of water, and thus, a maintenance problem.

Sealed cells incorporate an oxygen recombination (fuel cell type) electrode, which is electrically connected to the zinc electrode. Thus, any oxygen produced can be electrochemically reduced through discharge of the zinc electrode. This recombination in the sealed cell prevents the water loss discussed above, but the energy of recombination appears as heat, and a corresponding temperature rise. At 30% overcharge, a considerable quantity of heat can be produced. The oxygen-rich environment attacks the classical cellulosic membranes used in alkaline cells, so inorganic or fluorinated polymer spacers must be used in sealed systems.

On open circuit stand, hydrogen is generated from the corrosion of the zinc in alkali. Also, hydrogen is produced if a cell is overcharged. This hydrogen must be vented or recombined, again involving a water loss or thermal problem.

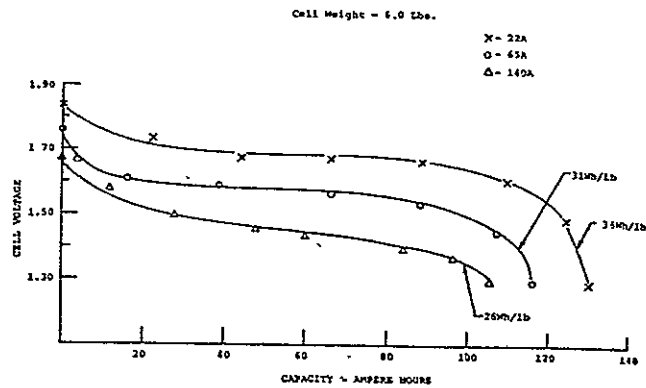
Upon cycling, there are considerable changes in the distribution of zinc over the zinc electrode. These shape changes, due to concentration gradients and gravity effects, greatly affect cell performance and eventually cause failure. Nickel electrodes of high surface area, which allows for good capacity, have a decrease in performance at high depths of discharge. At discharges to capacity depths of a practical nature, cycle lives have been in the region of 200 cycles for sealed cells and less for vented cells (8). A goal of 500 cycles is probably quite possible for electric vehicles applications.

Various procedures for using a third electrode (9) and mechanical wiping of the zinc electrode with windshield wipers (10) have been proposed to circumvent the problems discussed above. These do not, at their present state of development, appear to be practical.

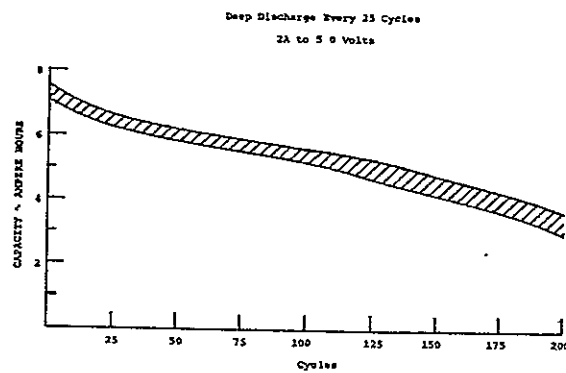
Figure 2.3-1

Typical Discharge Curves for Nickel-Zinc Batteries

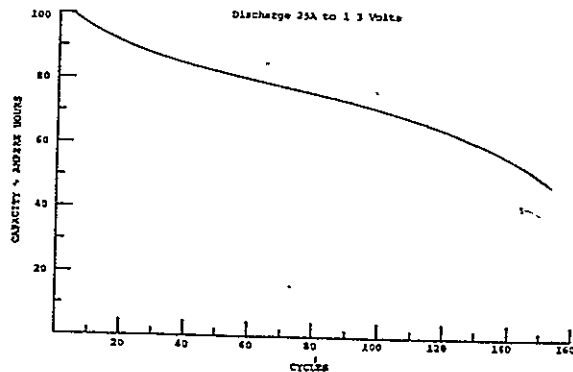
• 100 Ahr Nickel-Zinc Cell Performance



• Capacity Maintenance of 7 Ahr Sealed Nickel-Zinc Batteries



• Capacity Maintenance of 100 Ahr Vented Nickel-Zinc Batteries



In cost and energy density, a nickel-zinc battery is intermediate between a nickel-cadmium and lead-acid battery. Its demonstrated (and potential) cycle life is less than the above batteries. These features together with the low turn-around efficiency and . . . maintenance or thermal problems make it a poor candidate for energy storage systems.

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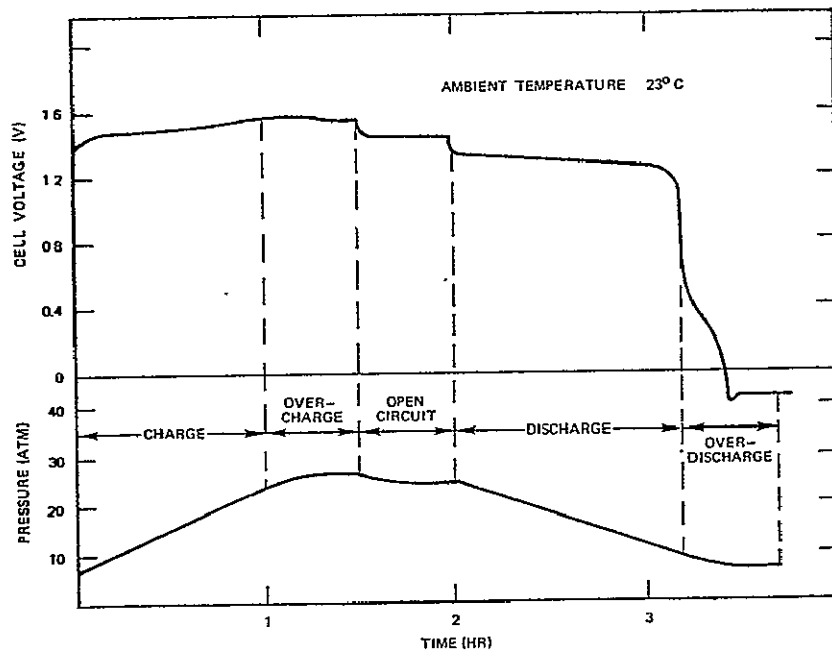
## 2.4 Nickel-Hydrogen Batteries

The nickel-hydrogen battery uses a nickel cathode from nickel cell batteries coupled with a hydrogen electrode from fuel cells. A KOH electrolyte is held in a matrix between the electrodes. In its aerospace application, the hydrogen electrode is catalyzed with noble metals (Pt, Pd, etc.). Other less expensive, but lower performance, hydrogen catalysts, such as nickel, could be used in energy storage applications. Catalyst substitution involves a performance and cost trade-off.

A charge-discharge curve for a Comsat cell is shown in Figure 2.4-1 (1) for the C rate (1 hr. charge/1 hr. discharge + over-charge). The hydrogen pressure changes are also shown.

Figure 2.4-1

Typical Ni-H<sub>2</sub> Cell Pressure and Voltage Characteristics



The reactions of the cell are shown in Table 2.4-1.

Table 2.4-1  
Electrochemical Reactions

Normal Operation		
Nickel electrode	$\text{NiOOH} + \text{H}_2\text{O} + \text{e}^- \xrightleftharpoons[\text{charge}]{\text{discharge}} \text{Ni(OH)}_2 + \text{OH}^-$	(1)
Hydrogen electrode	$\frac{1}{2}\text{H}_2 + \text{OH}^- \xrightleftharpoons[\text{charge}]{\text{discharge}} \text{H}_2\text{O} + \text{e}^-$	(2)
Net reaction	$\frac{1}{2}\text{H}_2 + \text{NiOOH} \xrightleftharpoons[\text{charge}]{\text{discharge}} \text{Ni(OH)}_2$	(3)
Overcharge		
Nickel electrode	$2\text{OH}^- \rightarrow 2\text{e}^- + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O}$	(4)
Hydrogen electrode	$2\text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^- + \text{H}_2$	(5)
Chemical recombination of O <sub>2</sub>	$\frac{1}{2}\text{O}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O}$	(6)
Reversal		
Nickel electrode	$\text{H}_2\text{O} + \text{e}^- \rightarrow \text{OH}^- + \frac{1}{2}\text{H}_2$	(7)
Hydrogen electrode	$\frac{1}{2}\text{H}_2 + \text{OH}^- \rightarrow \text{e}^- + \text{H}_2\text{O}$	(8)

During charge, the nickel electrode is 70 to 90% efficient. The inefficiency appears effectively as oxygen evolution. In this cell, however, the oxygen recombines with the hydrogen on the hydrogen electrode, so there is no water or oxygen loss. The energy for this "over-charge" effectively appears as heat. Up to 30% excess ampere-hours must be supplied to return the battery to its original state of charge. The resulting turn-around efficiency is, considering the charge/discharge voltages and "the over-charge factor," in the range of 55 to 65%.

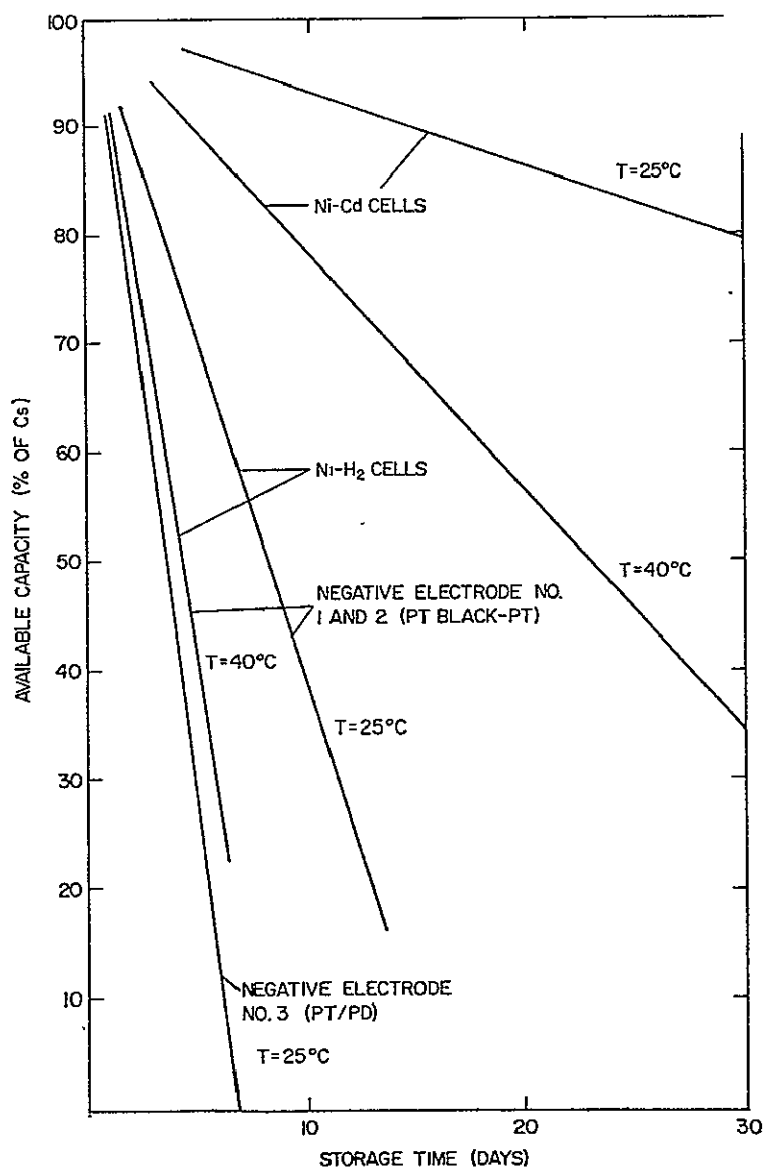
The nickel-hydrogen cell cannot be over-discharged if there is an excess of hydrogen in the system. The hydrogen produced at the completely discharged nickel electrode is equally consumed at the hydrogen electrode.

The pressure or volume of hydrogen provides a measure of the effective state of charge of the battery, a unique feature. Unfortunately, the presence of hydrogen accelerates the self-discharge. Hydrogen is rapidly chemisorbed on the NiOOH electrode, but the direct reduction of the NiOOH is slow, chemically. Comsat (1) reports a 20% loss of capacity

in the first day and then a slower loss. SAFT (2) reports a somewhat lower rate, 6 to 12% per day. SAFT Ni/Cd batteries with nickel electrode materials have a self-discharge in the range of 0.07 to 0.3% per day, Figure 2.4-2.

Figure 2.4-2

Charge Retention vs. Storage Time and  
Temperature for Ni-Cd and Ni-H<sub>2</sub> Cells



This rate of self-discharge of nickel/hydrogen batteries would be intolerable for energy storage purposes. A means would have to be found to remove or reduce the pressure of hydrogen in the cell. This would increase system complexity.

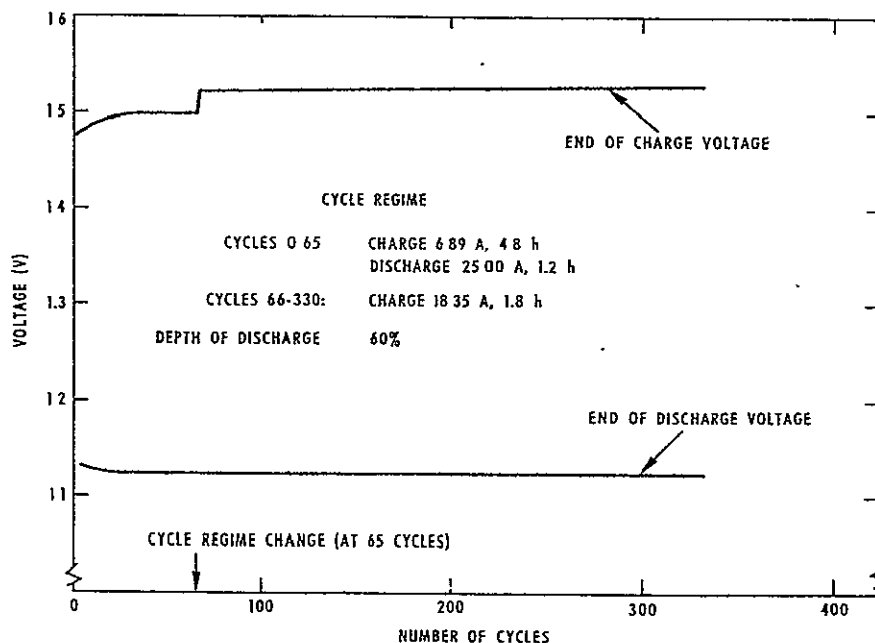
Pressure ranges of 300 to 400 psi hydrogen are used in aerospace cells. This would present a very definite hazard for energy storage system. A 100 MWH system would have 40 million liters of  $H_2$  (STP) stored under pressure (1.5 million liters of 450 psi gas).

Hydrogen could be stored reversibly as a metal hydride in the system, reducing the effective hydrogen pressure, but this would add to the cost of the system and the complexity. The release of hydrogen gas from metal hydrides requires the input of thermal energy. While there is waste heat from the cells, it is at a temperature level too low for effective hydrogen release. Heating processes would be required with a loss of efficiency.

If a nickel electrode of the type used in long-life Ni/Cd batteries is used, there is ample reason to believe that a cycle life greater than 5,000 hours (equivalent to Ni/Cd batteries) could be obtained. Comsat (1) reports lives of over 2,300 cycles with fuel cell type separators and 85% depth of discharge/cycle. At 25% depth of discharge, some cells have over 10,000 cycles. A cycle test of a SAFT cell is shown in Figure 2.4-3. The main failure modes over those of a Ni/Cd are mechanical changes in the  $H_2$  electrode due to gas evolution.

Figure 2.4-3

Voltage Behavior During Cycling of  
a Light Weight Ni- $H_2$  Cell





Energy Research Corporation has projected an advanced nickel electrode for the nickel-hydrogen battery. This electrode uses a graphite substrate for the support of the active nickel oxides. The oxidization of the carbon apparently limits the cycle life of this electrode, however. ERC projects that, with a transition metal catalyzed hydrogen electrode, a nickel-hydrogen battery for load leveling would cost in the range of \$37/KWH. Cycle life problems must be resolved before serious consideration can be given to this approach.

While the Ni/H<sub>2</sub> cell is attractive for its light weight compared to Ni/Cd, there is nothing to recommend it over Ni/Cd for energy storage. Ni/Cd batteries have been eliminated from massive energy storage systems already, on the basis of their greater cost than lead-acid batteries. The nickel electrode is the same as a Ni/Cd electrode. A hydrogen electrode suitably catalyzed is currently more expensive than a Cd electrode. Miller (3) of Eagle-Picher estimates that even with their low cost non-aerospace multi-cell battery design, the projected cost would range from 25% greater to 50 less than a comparable sealed Ni/Cd system. Further, the turn-around efficiency is less and the self-discharge rate is in an order of magnitude greater for the nickel-hydrogen battery. Storage of large quantities of hydrogen under pressure is a hazard and hydride storage is costly and energy inefficient for this application.

Nickel hydrogen batteries as presently described are not a serious contender for large energy storage systems.

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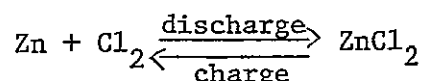
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## 2.5 Zinc-Chlorine Batteries

When zinc-chlorine batteries were first considered, the hazards of using gaseous chlorine, particularly in an electric vehicle, nearly precluded their use. P. Symons (1) of Hooker developed the technique of forming solid chlorine hydrate from chlorine and water. It is safe and easy to handle at near ambient temperatures. This led to the serious consideration of a zinc-chlorine battery with external storage of the chlorine as a hydrate. Energy Development Associates (EDA) has been developing the zinc chlorine battery for several years (2-7). It has now been selected for test in the BEST facility (8).

The zinc-chlorine cell with circulating electrolytes, soluble zinc anodes and gaseous or gas-type cathodes, has many analogies to the zinc-air cell and should be noted for comparison.

The overall cell reaction is relatively simple, namely:



and the theoretical cell voltage for this reaction is 2.12 volts, comparable to that for the lead dioxide-lead battery system.

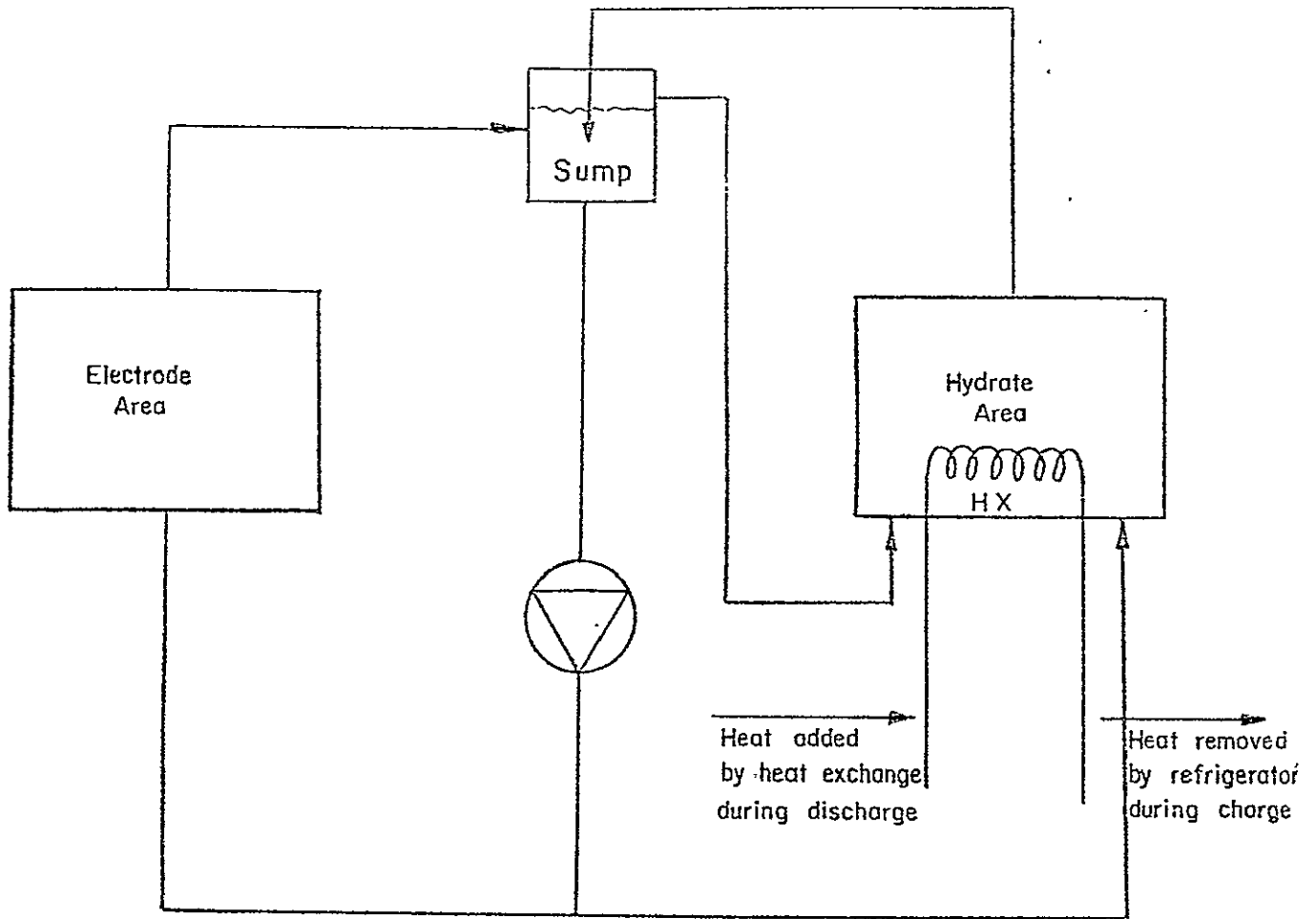
During discharge zinc is oxidized at the negative electrode, and chlorine, in a solution of zinc chloride, is reduced at the positive electrode. The oxidized zinc is soluble in the zinc chloride electrolyte. Thus, a clean zinc surface is always present, in contrast to zinc electrodes in alkaline electrolytes which become covered with a zinc hydroxide film. During charge, the reaction is reversed and the zinc chloride formed on discharge reverts back to zinc metal and chlorine gas is dissolved in the electrolyte.

During operation, the electrolyte is circulated through the cells. In discharge,  $\text{Cl}_2$  is added to the electrolyte external to the cell and during charge, the chlorine produced is dissolved in the circulating electrolyte and carried away for external storage. A simplified system schematic is shown in Figure 2.5-1 for the hydrate storage. The chlorine can be stored outside the battery in the form of the hydrate,  $\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ , which is a yellow, crystalline solid at temperatures below about  $10^\circ\text{C}$ . Above this temperature, the hydrate decomposes to give chlorine and water and the chlorine is permitted to react at the electrode surfaces. With an external store, and the need to lower the temperature below  $10^\circ\text{C}$  to produce the chlorine hydrate, an electrolyte circulation system with some form of heat exchanger is necessary. The hydrate formation is an endothermic process so the temperature changes of the system during cycling are low.

The electrode stack and the chlorine hydrate store are operated at about  $0$  to  $5^\circ\text{C}$ , and only a single electrolyte loop is needed between the stack and store. The heat exchanger used to cool the electrolyte is operated both

Figure 2.5-1

Simplified System Schematic  
for Zinc-Chlorine Battery



during charge and discharge. During discharge, the heat removed from the electrolyte coming from the stack is used to decompose the hydrate in the store before it circulates to the stack. This ensures that a smaller heat exchanger (refrigerator) can be utilized in this mode of operation because it is being operated in a more efficient manner.

In principle, the battery cannot be over-discharged (with excess chlorine in the system). When all of the zinc is removed from the electrodes, chlorine will be evolved and will cycle between the anode and cathode--an inefficiency on over-charge. When all of the zinc and chloride are exhausted, the resistance of the cell rises sharply and water is decomposed at high voltage, an easily detected signal. Also, the catalysts on the electrodes and the plating additives could be destroyed.

The discharge voltage at constant current is nearly constant for the total capacity of the battery. Similarly, for the charge, since the reactant concentration, electrolyte composition and inter-electrode distance do not change appreciably during cycling. Also, the temperature is controlled, because of hydrate storage requirements. This could allow constant power operation.

The highest reported achievement of the zinc-chlorine cell is the test operation of a Chevrolet Vega (3). This was a 60 KWH, 16 KW system with an energy density of 20 WH/lb. The performance curves for single cells and for a 24 cell bipolar stack are shown in Figures 2.5-2 and 2.5-3. A relatively high resistance is seen. This is due primarily to the low conductivity of the  $ZnCl_2$  electrolyte. These data were obtained using carbon-type electrodes.

Figure 2.5-2

Zinc-Chlorine Battery Performance

• Discharge of 24-Cell Submodule

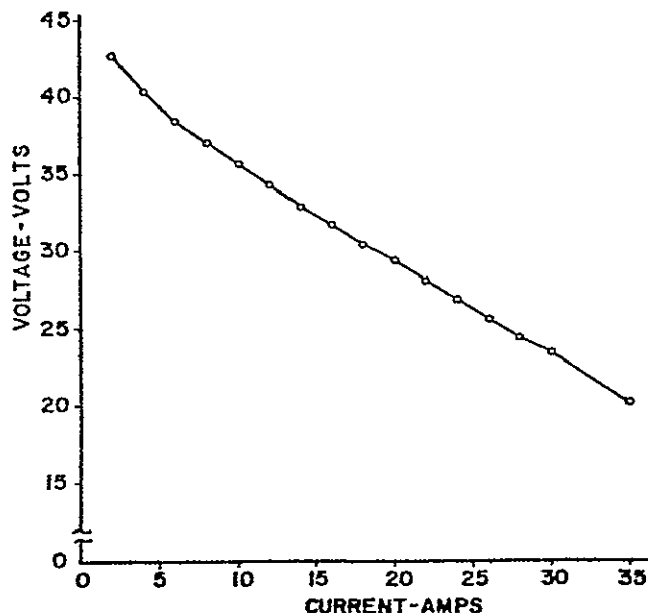
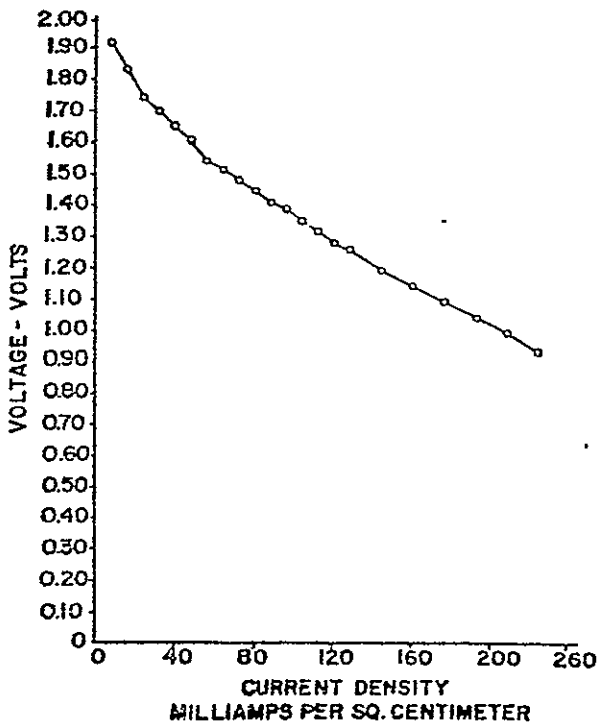


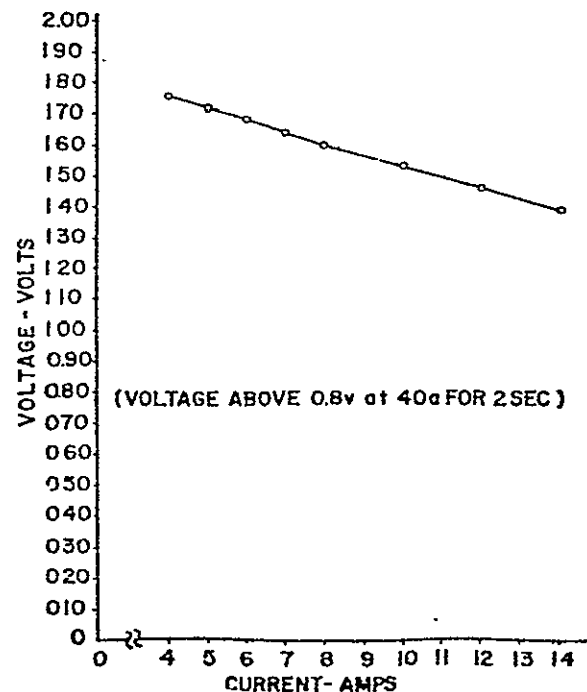
Figure 2.5-3

Zinc-Chlorine Battery Characteristics

• Discharge of Single-Cell Battery



• Discharge of One Cell of 24-Cell Submodule



Early versions of the zinc-chlorine hydrate battery used graphite substrates for both the zinc and chlorine electrodes; zinc was deposited on the graphite to form the negative electrode, and porous graphite was used for the positives. More recently, the larger batteries at least use noble metal catalyzed titanium electrodes instead of graphite. Zinc is deposited on titanium foil to form the negatives, while porous titanium sheets are used as the substrates for the positives. Advantages of using titanium instead of graphite are that it is easier to fabricate and join, it is lighter, and polarization losses are less for a given current density. It also has longer life than the porous carbon or graphite used before.

There has been little published on energy density and other factors that relate to energy storage applications. An electric vehicle paper (6) gave estimates for a 50 KWH vehicular battery (4 hour rate) as:

Energy delivered at four hour rate	50 kwhr
Average power to load	12.5 kw
Peak power for 30s	40 kw
Peak power for 2s	50 kw
Total weight	700 lb
Total volume	10.1 cu ft
Energy per unit weight at four hour rate	71.3 watt hr/lb
Energy per unit volume at four hour rate	2.86 watt hr/in <sup>3</sup>
Peak power density for 30s	57.2 watt/lb →
Peak power density for 2s	71.4 watt/lb

These values were derived from the parametric estimates shown below:

Summary of Total Battery Volume

<u>Component</u>	<u>Volume (liter)</u>	
Components inside battery case	170.6	
Hydrate store insulation	66	
Allowance for packing density inside case	14.6	
Case	4.9	
Refrigerator/condenser/fan	30	Manufacturers Literature
Total volume excluded by battery	286.1	

Summary of Total Battery Weight

<u>Component</u>	<u>kg/50 kwhr delivered</u>	
All active battery components	272	See Table 3
Insulation	2	
Case	38	
Brackets	4	
Total battery weight	318	

Volumes of Fully Discharge System

<u>Component</u>	<u>kg/50 kwhr delivered</u>	<u>s/g</u>	<u>liter/50 kwhr delivered</u>
40% $ZnCl_2$ 6.968 g/amp hr	186.53	1.42	131.36
Electrodes	as in fully charged condition		4.20
Electrode supports	as in fully charged condition		12.60
Hydrate store hx and store structure	as in fully charged condition		13.06
Pump, motor, sump	as in fully charged condition		4.80
Total for components inside battery case:			166.02



Volumes of Fully Charged System

<u>Component</u>	<u>kg/50 kwhr delivered</u>	<u>s.g.</u>	<u>liter/50 kwhr delivered</u>
Zn 1.220 g/amp hr	32.66	7	4.66
Chlorine hydrate store contents	3.655 cm <sup>3</sup> /amp hr		97.84
10% Electrolyte in cell stack spaces and plumbing 1.362 g/amp hr	36.46	1.09	33.45
Electrodes 0.41 g/amp hr	18.90	4.5	4.20
Electrodes supports 0.71 g/amp hr	18.90	(1.5)	12.60
Hydrate store hx and store structure 0.732 g/amp hr	19.6	(1.5)	13.06
Pump, motor, sump	12	(2.5)	4.80
Total for components inside battery case			170.61

Component Weight Summary

	<u>Weight (kg)</u>
50 kwhr battery electrolyte, electrodes, frames and hydrate Hx.	237
0.86 kwhr for pump	4
Pump and Motor	4
Sump and Main Plumbing	4
Refrigerator Compressor	14
Condenser and Fan	9
	<u>272</u>

The energy storage system would have different characteristics. An estimate included in the BEST conceptual design (9) indicated a 100 KWH bipolar, 50 cell module to weigh 250 lbs. (dry). The electrolyte (40%  $\text{ZnCl}_2$ ), at 7 grams per ampere hours, would add 750 pounds. To this must be added heat exchangers, pumps,  $\text{Cl}_2$  store, etc.

Little has been reported on the efficiency of the system. The above estimate for a car battery assumed 95% efficiency. There is little hard data available to substantiate this value.

Presently, EDA is testing an energy storage system under contract to EPRI. It is a single cell monopolar construction. Weaver (8), who observed its operation, reports 75% energy efficiency, with a useful coulombic efficiency of 83%.

There have been no reports by EDA on cycle life of zinc-chlorine systems. There is some data on 200 cycles on single cells (5). The final report on the EPRI-sponsored work has not been issued.

The costs of a zinc-chlorine system are hard to determine. The intrinsic cost of zinc chloride is low, but the rest of the system is an unknown. One simple costing approach would be to take Symons' (6) estimate for the car battery total system of 70 WH/lb and add an estimated manufacturing cost of 1.50 \$/lb. This gives a cost of \$21/KWH - an obviously low cost.

The cost associated with handling chlorine presents a great question. Bechtel is studying the engineering and cost questions of various methods of storing chlorine for the BEST facility and EPRI. Their report is due in the fall of 1976. A major cost consideration in the present approach is the use of a modified DSA-type electrode for the chlorine electrode. This requires noble metal catalysts on titanium. The noble metal costs for a chlorine electrode are in the range of 2.50 \$/ft<sup>2</sup> for a thin coating. At 40 ASF current density and 1.9 volts, the system needs 10.5 ft<sup>2</sup> of chlorine electrode per KW. This is equivalent to 26 \$/KW for noble metal. At a 4 hour discharge rate, this is 7 \$/KWH for noble metal. The use of a porous titanium substrate and the deposition of noble metal on the substrate at low loadings will, based on fuel cell experience, bring the cost for chlorine electrodes to something in the \$20/KW range. The zinc electrode, if uncatalyzed, could be in the \$5/KW range.

Until there are more definitive data on the zinc-chlorine energy storage system, one cannot make serious cost estimates. The simple cost analysis makes it appear to be in excess of 40 \$/KWH.

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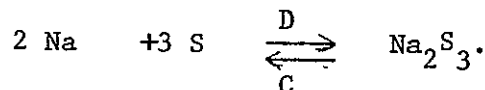
## 2.6 Sodium-Sulfur Battery Systems

A decade ago, Ford Motor Company announced the first technical description of a sodium-sulfur battery. The implied high energy and power density was encouraging for electric vehicles. Many organizations joined in the investigations. A prototype electric vehicle battery was demonstrated in England recently. The emphasis has now shifted to load leveling applications. Major work is being done by GE (1), Ford (2), Dow (3), and TRW (4). Na/S systems by GE and TRW are being considered for the BEST facility (5).

The sodium systems have recently been reviewed in some detail (6). The principle characteristics of the different cells are shown in Table 2.6-1.

Sodium-sulfur cells use electrochemically active materials at elevated temperatures (100-350°C). The active materials comprise liquid sulfur (with graphite to improve electrical conductivity) as the positive electrode, and liquid sodium as the negative electrode. A sodium-ion conducting barrier is needed to prevent the materials from reacting directly and shorting out the cell electronically. The lower temperature limit for operation mentioned above is determined by the melting point of the sodium polysulfides which are formed on discharge. The upper temperature limit is determined by the boiling point of the sulfur electrode.

The overall cell reactions are:



During discharge, elemental sodium is ionized at the solid electrolyte interface, and the sodium ions migrate through the solid ceramic electrolyte to the sulfur compartment. A reaction occurs to form polysulfide ions which are subsequently discharged to complete the electron flow. During charging, the reactions are reversed as shown. The open-circuit voltage for the charged cell is about 2.08 volts, while at 100 percent discharge, the open-circuit voltage is about 1.80 volts. The cell operating voltage on charge and discharge is proportional to the cell current.

Some performance curves and cell construction of the Ford cell (2) are shown in Figures 2.6-1 and 2.6-2.

The liquid electrode materials allow, in principle, completely renewable electrodes on charge and discharge - no dendrites or solid phase change. The solid electrolyte prevents self-discharge and, thus, the hot shelf life should be very long. At high temperatures, there is very little polarization.

Multi-cell stacks can present a problem. When a cell is "over-discharged",  $\text{Na}_2\text{S}_2$  is formed, the resistance increases and the local temperature rises. This is very detrimental to the solid electrolyte.

Table 2.6-1

Preferred Options For The High-Temperature Sodium Systems

Component	Dow <sup>1</sup>	Ford <sup>1</sup>	GE <sup>1</sup>	TRW <sup>1</sup>
Positive Electrode	S	S	S	S
Electrolyte	Borate	$\beta''\text{-Al}_2\text{O}_3$	$\beta\text{-Al}_2\text{O}_3$	MgO doped
	Glass			$\beta\text{-Al}_2\text{O}_3$
Negative Electrode	Na	Na	Na	Na
Current Collector	Graphite	Graphite	Graphite	Graphite
	Felt	Felt	Felt	Felt
Cell Case	Aluminum	Sulfide and	Coated	Stainless
		Oxide Coatings on Titanium	Aluminum	Steel
Design-Electrolyte	Capillary Tubes	Tubes	Tube	Disc
Present Laboratory Cell Size	(5-40AH)	(50-60AH)	(17AH)	(20AH)

Figure 2.6-1

Characteristics of Ford Na/S Cells

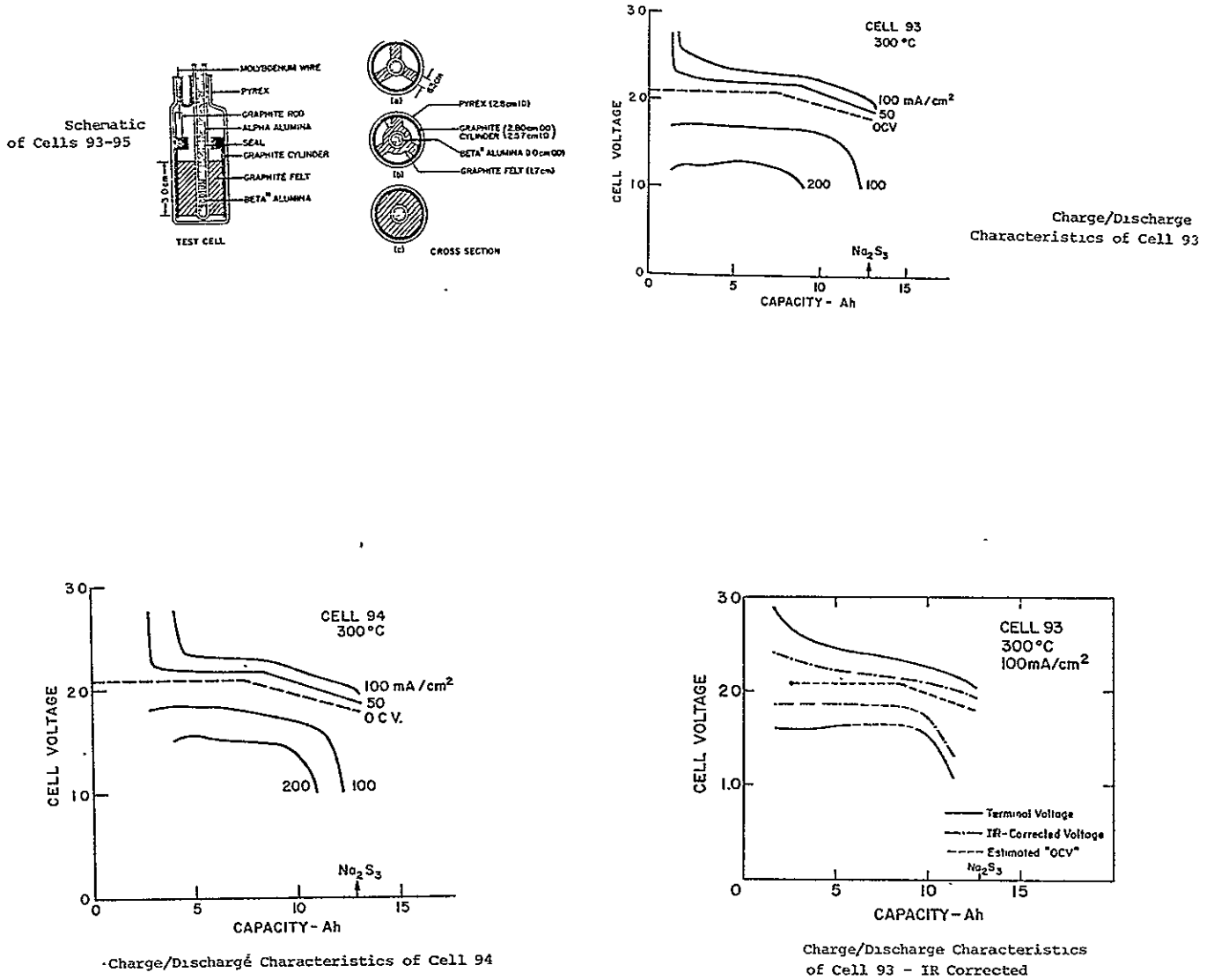
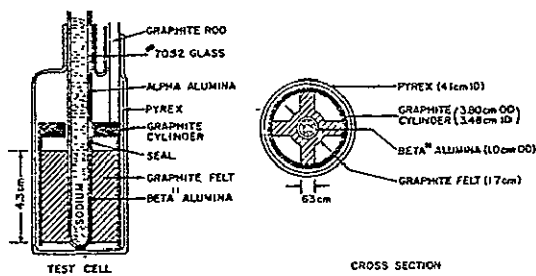
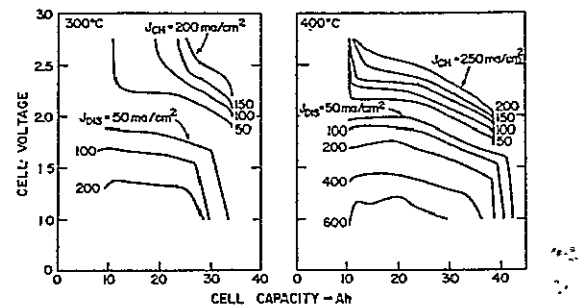


Figure 2.6-2

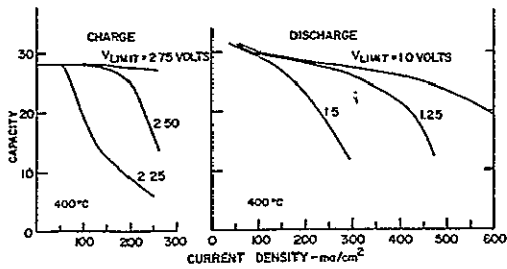
Additional Data on Ford Na/S Cells



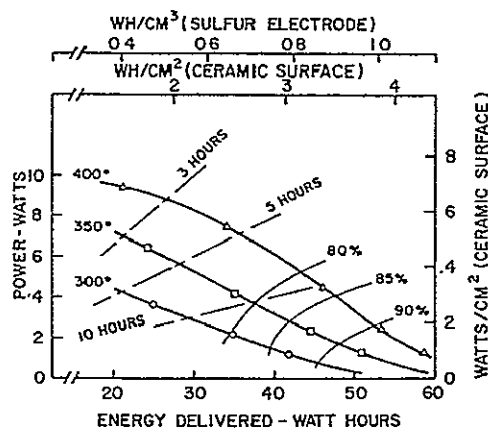
Schematic of Cell 89



Charge/Discharge Characteristics of Cell 89



Effect of Cell Voltage Limits on Cell 89



Performance Characteristics of Cell 89

Two types of barrier (solid electrolyte) have evolved: (1) beta-alumina ( $\text{B-Al}_2\text{O}_3$ ) type materials, and (b) sodium-ion conducting glasses. Most emphasis has been placed on battery systems incorporating (a) for energy storage applications. The sodium conductive glasses have a conductivity of  $10^4$  ohm-cm but are used in 10 micron thickness as electrolyte. The alumina, while more conductive, about 15 ohm-cm, is used in 1 mm thicknesses.

The problems with beta alumina are discontinuous grain growth, reproducibility and successful cell operation. Good electrolytes are now being fabricated. These are good in physical-electrical properties. That is, electrochemical sodium transfer from a sodium to sodium electrode is good. But the long term performance of complete cells is poor.

Many different types of beta alumina are being investigated: beta, beta double prime and MgO-doped, together with flat plate vs tube designs. CGE in France has shown that MgO-doped material, while having good conductivity, has short life. They have demonstrated a sodium transfer of over 2000 hours for pure beta alumina, at less than  $100 \text{ ma/cm}^2$ . There is considerable disagreement as to the best form for the electrolyte. Seals at the electrolyte/walls are a problem that has not been solved.

The glass electrolytes, though fabricated by production techniques, and of low cost, have a high failure rate. A 5 ampere hour cell has 3 to 6000 glass tubes (8cm long, 70-80 micron diameter and 10 micron wall thickness). Life is in the range of a few weeks.

The efficiency of a sodium-sulfur cell can be high, about 80% on discharge. Fortunately, at this general efficiency region, the ohmic losses can maintain the cell temperature at lower rates of discharge (higher efficiency); auxiliary heating may be required. The combined electrical and thermal efficiency is a major factor in all high temperature cells.

As far as volumetric density is concerned, the GE batteries for the BEST<sub>3</sub> Facility were estimated to be  $88 \text{ Kwh/M}^3$ , while the TRW System is  $87 \text{ Kwh/M}^3$  (5). More detailed studies are needed to define system size adequately.

The real cost of a sodium-sulfur cell is a very difficult number to determine. Because no one has really demonstrated a workable sodium-sulfur cell, all cost projections are conjectural, at best.

The corrosion of the cell case is a major problem. There has been no demonstration of an economically viable material for the positive electrode case (6). There is no consensus of the suitable case material, as shown by the various approaches listed previously in Table 2.6-1.



The current collectors currently used by all investigators are carbon felts or cloths. At present, this is the only suitable material. Its cost, however, could be high. The current cost of graphite felt is in the range of 80 \$/lb. Some investigators project an order of magnitude or more reduction in cost, others are not as optimistic.

Beta alumina costs are also high, with current estimates at the 25 \$/lb. level. Because ceramics are low in cost generally, a price reduction in the future is a reasonable assumption. However, the type of alumina has not been selected and the processing steps needed to get a good electrolyte are not known. The projections of 25 ¢/lb. used to arrive at the estimated low materials costs of the cells is a pure guess. In the annual review of the Ford work for NSF, the following costs were given:

Major Materials Costs for Laboratory Cells

<u>Material</u>	<u>Cost</u> <u>(\$/lb)</u>	<u>Amount</u> <u>(gm/cm<sup>2</sup> of <math>\beta</math>-Alumina)</u>	<u>Cost</u> <u>(\$/kWh)</u>
Graphite felt	75	0.091	6.57
Stainless Steel	2	2.53	4.86
$\alpha$ -Alumina Header	10	0.35	3.18
$\beta$ -Alumina		0.32	50.46
Sodium	0.4	2.06	0.79
Sulfur	0.1	3.71	0.36
		Total	62.22

A materials usage efficiency of 100% has been assumed, and all costs are in terms of unit area of ceramic electrolyte. To convert free electrolyte area to kWh, a factor of 2.5 Wh/cm<sup>2</sup>, or 435 cm<sup>2</sup> ceramic electrolyte per kWh has been used. This has been obtained in cells designed for load leveling. At \$20/kWh, a 1,000 lb. Na-S energy cell with 12 W/lb and 120 Wh/lb would cost \$2,400. An order of magnitude reduction in felt and ceramic costs is needed to reach targets of 20 \$/KwH.

GE, projecting the costs of materials, gives the following estimate (8):

<u>CELL COSTS</u>	<u>\$ Per KWh</u>	
Sodium (22.5¢/lb)	0.28	
Sulfur (8¢/lb)	0.21	
beta-Alumina (25¢/lb)	0.44	
Graphite (\$10/lb)	0.44	
Aluminum Sheet (63¢/lb)	0.93	
Insulating Header Material	<u>0.18</u>	2.48
<u>MODULE COSTS</u> (Based on 62.5 KWh units)		
Steel Sheet	0.80	
Thermal Controls	0.56	
Insulation	<u>0.24</u>	<u>1.60</u>
TOTAL		<u>4.08</u>

There is no real basis for projecting a cost for large-scale Na/S cells. There are too many technical problems yet to be defined and resolved. If we take the old myth of a dollar a pound, then sodium-sulfur could be in the range of \$20-\$30/Kwh. But, the present real world price for limited life single cells is orders of magnitude higher.

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## 2.7 Lithium-Chlorine Batteries

Lithium-chlorine batteries using molten lithium anodes, a fused mixture of lithium and potassium chlorides at above 350°C as the electrolyte (or lithium chloride at 650°C) and gaseous chlorine or graphite as the cathode have been studied in the past. The energy density was projected to be very interesting (1). General Motors (1-4) has reported the highest power density and specific power of any battery, 20 A/cm<sup>2</sup> at 2 volts with lithium chloride electrolyte at 650°C. A few hundred cycles on a single cell were demonstrated with venting of Cl<sub>2</sub> on charge and use of fresh Cl<sub>2</sub> for discharge. The anode substrates were stainless steel or nickel and the cathodes were porous carbons. The turn-around efficiency of the cells was in the range of 90%.

Cell failure was traceable to failed seals, impurities in the electrolyte and flooding of the porous carbon electrode. The major technical problem, other than materials stability, is a reversible gaseous Cl<sub>2</sub> electrode. A direct analogy exists between this problem and those of a reversible oxygen electrode for air cells. The application being considered by General Motors was electric vehicle power. Considerations of vibration, safety, etc., demanded a hot seal. This is a positive seal of metal to ceramic with its associated problems. A cold seal possibly could be used for stationary energy storage application. In a cold seal, the conductive flanges of the electrodes are cooled with circulating water. This freezes the molten salt between the flanges and this provides a non-electrically conductive seal. The reliability of cooling water supply is most critical.

The problems of safely storing the Cl<sub>2</sub> evolved from the cell at high temperature, the corrosive nature of Cl<sub>2</sub> at high temperatures, and the severe hazards of some cell malfunctions caused General Motors to stop their investigations of lithium-chlorine cells for mobile applications.

Present active investigations of lithium-chlorine batteries are limited to reserve primary batteries for torpedo power (5). Here, the need for high power density and energy for naval applications, together with limited life of the application, can justify living with the problems discussed above.

The apparent technical battery problems and the hazards of storage and use of large volumes of chlorine in a high temperature cell system prevent serious consideration of a lithium-chlorine battery for energy storage use at this time.

Bechtel is studying the storage and handling of large quantities of chlorine for energy storage purposes for EPRI. If they find low cost, reliable methods of storing and processing chlorine and if the materials information on high temperature lithium-metal sulfide batteries becomes more positive, it may be possible later to reconsider a lithium-chlorine energy storage system.

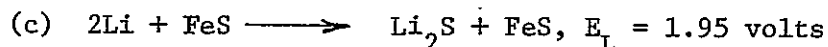
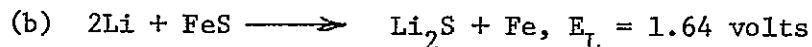
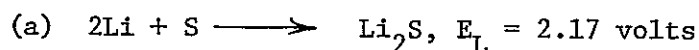
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## 2.8 Lithium-Sulfur Batteries

Lithium-sulfur type batteries are in the same general family as the sodium-sulfur batteries. The electrodes are molten, and high temperatures are required to have good electrolyte conductivity. Several organizations are investigating lithium-sulfur batteries for load leveling applications: Atomics International (AI) (1), Argonne National Laboratories (ANL) (2) and General Motors (3). These investigations started in the late 1960's. All the systems use KCL/LiCl eutectic at 400-450°C as the electrolyte. Elemental sulfur has a high vapor pressure at these temperatures and the polysulfides of lithium have appreciable solubility in the fused salt electrolyte. All the investigators have now gone to solid metal sulfides as the cathodes, but there is no universal consensus on the rest of the system. The various options are shown in Table 2.8-1 (4)

While liquid lithium gives higher current densities, there are solubility problems. Lithium alloys are now used for better current efficiency. Iron sulfides are used as cathode active materials because of their availability and relative low costs. The simplified cell reactions are:



where  $E_L$  is the cell voltage measured against a lithium reference electrode. The 50 percent aluminum alloyed with the lithium in the ANL cell to reduce its corrosivity does not contribute to the cell reactions, but lowers the above voltages by about 0.30 volt, hence, to simplify matters, this has been omitted from the three equations above. Replacing the sulfur electrode with an iron sulfide reduces the corrosion and compatibility problems which were originally encountered. Although efficiency, energy and power density, and cost are affected detrimentally, this is offset by the longer life obtained from the cells.  $\text{FeS}_2$  gives a higher cell voltage during initial discharge, and a higher energy density than FeS positives, although the watt-hour efficiency and utilization factor is similar for each. However, with the former expensive molybdenum current collectors are needed, while the latter only require iron collectors. The lower cost, greater availability and fabricability resulting from the use of iron collectors with FeS positives has caused emphasis to be shifted towards this combination of materials for energy storage batteries. At the present time one developer prefers to use FeS alone, while another prefers to use a mixture of FeS and  $\text{FeS}_2$ , i.e.,  $\text{FeS}_{1.5}$ .

Separators which are stable at high temperature (400°C) in corrosive environments are needed. Porous ceramics are generally required. The fabrication of these separators is an inherently expensive process, requiring a technology breakthrough for major cost reduction. The separator question is complex: flexible vs. rigid; stable vs. unstable to lithium, etc. Flexible

Table 2.8-1

Presently Preferred Options for the Lithium Systems

Component	AI	ANL	GM
Positive Electrode	FeS <sub>1.5</sub>	FeS <sub>2</sub> , FeS <sup>(a)</sup>	FeS <sub>2</sub>
Separator	Beo and Al <sub>2</sub> O <sub>3</sub> (rigid)	BN (Flexible)	AlN (rigid)
Negative Electrode	Li-Si	Li-Al	N.A.
Electrolyte	LiCl-KCl	LiCl-KCl	LiCl-KCl
Positive Current Collector	Carbon felt	Molybdenum	N.A.
Positive Lead	Molybdenum	Molybdenum	N.A.
Design - Electrode	Prismatic	Horizontal Prismatic	N.A.
Orientation (present lab. cell size)	(100 WH)	(200 WH)	
Feedthrough	Compression	Compression	N.A.
Case	SS (floating potential)	Iron (neg. elect. potential)	N.A.

<sup>(a)</sup> Additives of Cu<sub>2</sub>S, CoS<sub>2</sub>, and Co<sub>2</sub>S<sub>3</sub> are also utilized.

<sup>(b)</sup> Made from an aggregation of carbon particles which have been pressed together with a binder.

separators less volume, but rigid types are easier to fabricate. Flexible materials, such as BN and AlN, react with metallic lithium. While the lithium alloy reduces the activity of lithium, over-charge of cells can produce metallic lithium and lead to failure.

In general, high purity materials are required in these separators to prevent electronic conductivity. This also adds to the cost.

The workers at ANL have demonstrated a 70 WH/lb battery at the 10 hr rate in a 200 WH configuration. AI has demonstrated 1000 cycles for the sulfide electrode. AI has also shown several hundred cycles on Al-Si electrodes. ANL has demonstrated 3300 hours of charge/discharge at a 10-hour rate in a single cell. AI has demonstrated less than 100 cycles on their complete cell system. There has been a lot of progress, but a complete realistic long-life battery has not yet been demonstrated. Effort in this area is at an early stage of development.

The estimate of energy density is difficult to make. Preliminary design of the  $\text{Al}_3$  battery for BEST is rated at 200 KWH/M<sup>3</sup>, while the ANL system is 140 KWH/M<sup>3</sup>. These could probably be reduced in the future. The turn-around efficiency in well-designed cells should be about 80%.

The costs of the lithium-sulfide system are also difficult to predict. Various projections have been made, as discussed in Section 1. These are all very optimistic and impossible to judge, given the current fluid state of development. The final battery cost could range anywhere from \$20-100/KWH.

Both the lithium and sodium batteries are at a similar state of development and significant further work will be required before they can truly be evaluated for energy storage applications.



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## 2.9 Organic Electrolyte Secondary Batteries

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Alkali metals, which could provide high energy, low weight anodes, can not be used in aqueous secondary batteries. Thus, many investigators have gone to fused or molten salt electrolyte systems, in which the alkali metals can be used as secondary anodes. Unfortunately, these electrolytes require high temperatures to be conductive. Other investigators have considered electrolytes of salts dissolved in organic solvents. The solvents are chosen for their compatability with alkali metals. This approach would allow room temperature operation of high voltage couples.

Several successful primary battery systems using organic electrolytes have been demonstrated. The secondary battery aspects have, however, presented problems.

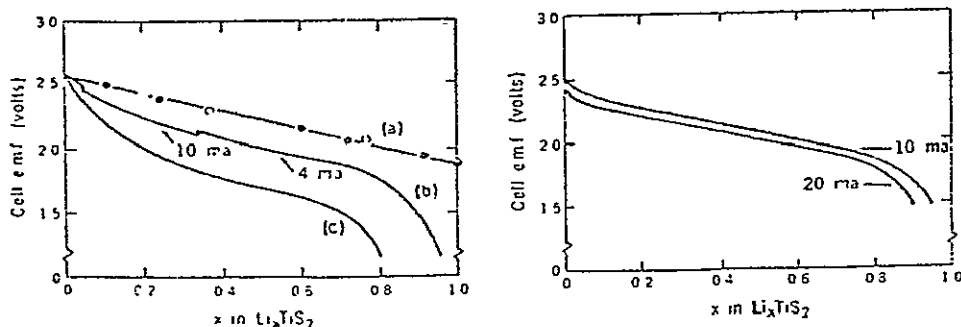
There are reports in the literature of cathode materials that have demonstrated reversibility when cycled as half-cells in organic electrolytes. These are generally transition metal chalcogenides (1-5). The problem presented to these investigators has been a reversible lithium anode in organic electrolytes. This problem was discussed in great detail at the Power Sources Conference in Brighton, England, in September 1974, in the presentation of a paper on lithium deposit morphology by Broadhead (6). It was concluded that development of a rechargeable lithium electrode was the single most important problem.

Whittingham (7,8) has recently discussed a secondary lithium battery in organic electrolytes using the cathode reaction of the intercalation of lithium into layered titanium sulfide. The reaction of the cathode was reversible and lithium ions were successfully plated and depleted at relatively high current density from electrolytes consisting of lithium perchlorate in mixtures of 30% dimethoxyethane and 70% tetrahydrofuran or lithium aluminum chloride in methyl chloroformate. The data are shown in Figure 2.9-1. The energy density computed from these data is 480 wh/kg. Shallow cycles of 4% of capacity gave over 1000 cycles.

No data were presented on other parameters of the system that would allow an estimation of the practical technical factors and costs for an energy storage system. While secondary organic electrolyte batteries are possible, evaluation of them for energy storage systems must await further data.

Figure 2.9-1

Performance Characteristics  
of  $\text{Li}/\text{TiS}_2$  Couple



(Left). Cell emf of  $\text{Li}/\text{TiS}_2$  couple. (Curve a) Open-circuit values obtained on discharge of  $(0)\text{TiS}_2$  and recharge of  $(0)\text{LiTiS}_2$ , (Curve b) values on discharge at 10 and 4 ma, and (Curve c) values on discharge after the 1100 cycles at 4 ma. The differences between the curves are mainly due to the resistance losses in the electrolyte associated with a large electrode separation.

(Right). Discharge characteristics in solution of lithium aluminum chloride in methylchloroformate.

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## 2.10 Summary

The preceeding sections have discussed in some detail the characteristics of several types of batteries which may be considered for large scale energy storage systems. The characteristics and estimates of the various batteries are summarized in Table 2.10-1.

- 89 -  
Table 2.10-1

Summary Assessment of Candidate Electrochemical Energy Storage Systems

Battery System Characteristics	Lead-Acid				Zn-Air	Ni-Zn	Ni-H <sub>2</sub>	Zn-Cl <sub>2</sub> (Hydrate)	Na-S (GE)	Na-S (TRW)	Li-FeS <sub>1.5</sub>	Li/Al-FeS	Organic Electrolyte
	ESB	Present GTD	Gould	Advanced									
Temperature, °C	10-60	10-60	10-60	10-60	<90	<60	<60	<80	285-420	285-420	300-450	350-450	Ambient
Open Circuit Voltage	2.09	2.09	2.09	2.09	1.65	1.71	1.36	2.12	2.08	2.08	2.05	1.32	3
Charge Voltage	2.3	2.3	2.3	2.3	2.4	1.9	1.5	2.23	2.35	2.75	2.4	1.55	NA
Maximum Charge Voltage	2.65	2.45	2.6	2.4	2.4	2.0	15	2.4(?)	2.50	2.75	2.7(?)	1.62	NA
Discharge Cutoff Voltage	1.7	1.7	1.7	1.7	0.9-1.0	>1.3	>1.25	1.90	1.60	1.60	1.0	0.85	NA
Minimum Voltage	1.3	1.3	1.3	1.3	0.8	1.0	1.0	1.5+0	1.00	1.0	0.1	0.65	NA
V <sub>c</sub> /V <sub>cod</sub>	1.58	1.44	1.58	1.4	2.67-2.4	1.46	1.20	1.17	1.47	1.53	2.4	1.82	--
Turn-around Efficiency	85-75	85-75	80-70	85-75	50-40	85	~80	90-70	~80	80	85-75	85-75	High
Energy Density, KWH/m <sup>3</sup>	5.5	51	50	120-60	160-110	90	60-50	175-85	270-90	270-90	280	140	NA
Power Density, KW/m <sup>3</sup> (10 hr rate)	55	5.1	5.0	12-6	16-11	9	6-5	17.5-8.5	27-9	27-9	28	14	NA
Life, yrs.	~10	~10	~7	~10	5	10-5	10-5	10-5	10-5	10-5	10-5	10-5	NA
Open Circuit Losses, %/day	1	1	1	1	Nil	1-2	0.1-1	~0	~0	~0	~0	~0	NA
Essential Materials	Pb Sb H <sub>2</sub> SO <sub>4</sub>	Pb Sb H <sub>2</sub> SO <sub>4</sub>	Pb Sb H <sub>2</sub> SO <sub>4</sub>	Pb Sb H <sub>2</sub> SO <sub>4</sub>	Zn KOH Catalysts?	Na Zn KOH	Ni N <sub>2</sub> Container	ZnCl <sub>2</sub> Ti Catalysts	Na C βAl <sub>2</sub> O <sub>3</sub>	Na C βAl <sub>2</sub> O <sub>3</sub> Glass	Li C Separators	Li BN Separators	Cathodes Li Organic Solvent
Essential Material Cost, \$/KWH	20	22	13	10-15	1	8	8-15	2-8	1.50-2	10-20	10-20	10-20	NA
Material Availability (E/Excellent, G/Good, F/Fair)	Pb G Sb F	Pb G Sb F	Pb G Sb F	Pb G Sb F	Zn G/E Cat G	Ni F Zn G/E	Ni F Catalysts F	ZnCl <sub>2</sub> G/E Ti F Noble Metals F	Na G/E C F/G	Na G/E C F/G	Li F C F/G	Li F BN F	NA
Hazards (1)	Low H <sub>2</sub> Acid	Low H <sub>2</sub> Acid	Low H <sub>2</sub> Acid	Low H <sub>2</sub> Acid	Low KOH	Low KOH H <sub>2</sub>	Medium H <sub>2</sub> Pressure	Medium High Cl <sub>2</sub> Acid	High Na (x) S (x) Temp Fire Exp	High Na (x) S (x) Temp Fire Exp	High Li (x) Temp Fire Exp	Medium Li/Al Temp Fire Exp	Medium Li(s) Organics

(1) Exp = explosion, + = favorable, - = unfavorable  
NA = not available.

- 90 -  
Table 2.10-1 (Cont'd)

Summary Assessment of Candidate Electrochemical Energy Storage Systems

Battery System Characteristics	Lead-Acid				Zn-Air	Ni-Zn	Ni-H <sub>2</sub>	Zn-Cl <sub>2</sub> (Hydrate)	Na-S (GE)	Na-S (TRW)	Li-FeS <sub>1.5</sub>	Li/Al-FeS	Organic Electrolyte
	ESB	C+B	Gould	Advanced									
Environmental Impact of System													
Normal Operation	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	Medium
Unusual Upset	Low	Low	Low	Low	Low	Low	Medium	Medium High	High	High	High	High	Medium
Constant Power Charge <sup>(1)</sup>													
Low Rates	+	+	+	+	+	+	+	+	+/-	+/-	+/-	+/-	-
High Rates	-	-	-	-	++	+	+	+	-	+	-	-	-
Salvage <sup>(1)</sup>	++	++	++	++	++	++	+	++	+/-	+/-	+/-	+/-	-
Auxiliaries	Air Pump Cooling	Air Pump Cooling	Air Pump Cooling	Air Pump Cooling	Pumps Compressors CO <sub>2</sub> Scrub	Cooling ?	Cooling ?	Pump Refrigerator	Heaters Exchangers	Heaters Exchangers	Heaters Exchangers	Heaters Exchangers	None
Maintenance Requirements	H <sub>2</sub> O Addition Cell Balancing  Coolant Loops	H <sub>2</sub> O Addition Cell Balancing  Coolant Loops	H <sub>2</sub> O Addition Cell Balancing  Coolant Loops	H <sub>2</sub> O Addition? Cell Balancing  Coolant Loops	CO <sub>2</sub> Scrubbers Pumps  Cell Balancing	Possible Air Pump H <sub>2</sub> O Addition Cell Balancing	Pressure Water Addition  Cell Balancing	Pumps Vents Refrigerator Plating Additives	Cooling Gas Circulator Cell Balancing	Cooling Gas Circulator Cell Balancing	Cooling Gas Circulator Cell Balancing	Cooling Gas Circulator Cell Balancing	(None)
Replacement Possibilities	Electrode Replacement	Electrode Replacement	Electrode Replacement	Electrode Replacement	Oxygen Electrode Replacement Retain ZnO	Renewal	Renewal	Cell Replacement Retain ZnCl <sub>2</sub>	Cell Replacement	Cell Replacement	Cell Replacement	Cell Replacement	Cell Replacement
Problem Areas	Gassing Utilization Excess Pb Adds Weight	Gassing Utilization Excess Pb Adds Weight	Gassing Utilization Excess Pb Adds Weight	Gas Recombiners	Shunt Currents Zinc Plating O <sub>2</sub> Electrode	Shape Change Zn Temperature Rise Gas'ing	Pressure Cost Of N <sub>2</sub> Electrode Water Redistribution	Shunt Currents Zn Plating Ti Cost Ru Cost	Seals High Temp Materials Life	Seals High Temp Materials Life	Seals High Temp Materials Life	Seals High Temp Materials Life	Life

(1) Exp = explosion, + = favorable, - = unfavorable  
NA = not available

### 3. MATERIALS AVAILABILITY, SALVAGE AND MANUFACTURE

#### 3.1 Introduction

The installation of large capacity energy storage systems will depend upon sufficient raw materials to manufacture the batteries and their auxiliaries. When energy storage systems are in large use, there would be a large amount of recycle of materials. This reduces the on-going demand for materials. On the other hand, materials which ordinarily are not recycled, would also now have to be recycled. Aside from economic reasons for recycling, the pollution and hazards problems associated with the disposal (dumping) of batteries will pose a problem. Even though the first costs of recycling may be higher than for new materials, the environmental effects may force collection of the used batteries and their recycle. This is a hidden cost presently unpredictable, which is not considered in present analyses.

#### 3.2 Lead-Acid Batteries

Lead, either as metal or alloy, or as oxide, constitutes the major material in lead-acid batteries. It constitutes about 75 percent of the weight, and represents typically some 25 to 50 percent of the manufactured price, depending on the battery type and volume of manufacture. The recycling of lead is standard practice in the industry today. However, the initial filling of the pipe-line (15 years) with lead in the energy storage system applications could strain available lead supplies. The amount of lead/antimony in various size systems is indicated below:

Units: Metric Tons

Metal Needed for 100 MWhr Stations:	<u>Lead</u>	<u>Antimony</u>
1	2,642	33.5
10	26,420	335
100	264,200	3,350
500	1,321,000	16,750

World Mine Production 1973 (10)

U.S.	547,000	1,158
Rest of the World	2,905,000	68,209
Total	3,452,000	69,209

World Reserves 1973 (11)	128,000,000	4,630,000
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The 100 MWhr 10 MW battery for the above analysis was composed of 5,255 cells of 10,000 Ahr rated capacity. The number of substations of this size which can be built before exceeding the 1973 mine production rate in any one year is thus 1,306 based on lead and 2,069 based on antimony, using a low antimony alloy battery design. Thus, large demand for lead-acid load leveling batteries will have an adverse effect on the balance of payments in the U.S. with only 16% of the mining production within the U.S. The prices of both lead and antimony are likely to rise significantly. It would also impact on other industries that use lead.

### 3.3 Zinc-Chlorine Hydrate Batteries

No problem is anticipated with the supply of zinc or zinc chloride. These are relatively abundant materials and their use in energy storage batteries is not expected to greatly impact the world supply. Zinc metal supply is related to lead availability which has already been discussed. The availability of titanium for both anode and cathode supporting structures/current collectors has not been determined. However, although platinum metal catalysts are not abundant in the United States, the amounts needed in oxide form to coat electrodes is relatively small and should not pose a problem.

### 3.4 Sodium-Sulfur Batteries

The raw materials required for the construction of sodium-sulfur batteries are relatively abundant and availability is not considered a pacing factor. The raw materials are also relatively inexpensive in cost. However, suitably processed beta-alumina-type ceramic electrolyte materials are presently difficult to obtain. In only a few companies have suitable properties been exhibited, usually under restrictive conditions of current density and temperature. Availability of fabricated beta-alumina components, whether doped or not to improve electrical properties, is seen as a limiting technology for this battery system.

The ceramic electrolyte possibly represents about one-third of the total cell cost. It will be economically advantageous to tailor the cell construction to the minimum amount of ceramic electrolyte that can be used without sacrificing life or performance. The greater the power density desired, then the larger the surface area of electrolyte needed. However, energy density is primarily a function of the active materials incorporated in each cell. The materials requirements for the sulfur electrodes are not known at this time because there is no consensus of opinion as to what is most satisfactory.

### 3.5 Lithium-Metal Sulfide Batteries

The material most scarce in availability is thought to be lithium. The world's total lithium supply in the year 2000 was estimated by the Foote Mineral Company to be about  $2.42 \times 10^7$  metric tons. The demand for lithium for electric vehicle and energy storage batteries by 2000 A.D. has been estimated by ANL to be about  $9.2 \times 10^5$  metric tons. This represents about 3.8 percent of the total supply which is not considered unreasonable. For off-peak energy storage alone, about  $8.5 \times 10^5$  metric tons of lithium will be required, or about 3.5 percent of the total supply.

Iron and sulfur are thought to be readily available, and problems with aluminum should not be encountered. Similarly, the lithium and potassium chloride salts required for the fused salt electrolyte should be available in sufficient quantity provided that the manufacturing capacity is installed.

### 3.6 Zinc-Air Batteries

There is an adequate supply of zinc. While noble metals are not required on the cathodes, improved performance may justify their use.

### 3.7 Manufacturability

The lead-acid batteries have well-known manufacturing techniques. Advances possible in lead-acid will only slightly modify the manufacture. Large-scale production will introduce more automation. The advanced batteries discussed above have not proceeded in R&D to the point where manufacturability can be rationally discussed. The materials of construction seals, types of solid electrolyte, catalyst loadings and distribution on porous electrodes, current leads for high temperatures batteries, general corrosion problems, purity requirements for life, etc., have not been determined. The solutions to these problems are unpredictable now and each solution will require different manufacturing techniques.

All things are manufacturable. It is a question of number of process steps, control and cost.

#### 4. BATTERY OPERATION AT CONSTANT POWER

In energy storage systems to store off-peak or solar power, there is a conflict between the normal electrical requirements or desires of the electric utility and the normal electrical characteristics of the batteries. The electric utility would desire to supply constant power to the battery charging facility during off-peak periods and would desire to receive constant power from the inverter/transformer of the battery energy storage facility during the on-peak periods. Battery systems, however, are dynamic systems. In general, the electrical characteristics during charge and discharge depend upon the state of charge, and since the state of charge is constantly changing during active use of the battery, there is a temporal factor in the electrical characteristics. The rate of charge and discharge will affect the electrical characteristics due to factors such as the particular electrochemical reactions of the battery couple, electrolyte concentration gradients, diffusion limitations, temperature changes, etc.

The "constant" power (in and out) desired by the utility is thus in conflict with the above non-constant properties of a battery system. The degree of conflict will depend upon the type of battery. Consider, for example, a lead-acid battery system. The characteristics of lead-acid batteries are relatively well known and can be analyzed. ESB has performed a fairly detailed analysis of charging lead-acid batteries for energy storage as part of a study for EPRI. The following discussion is, in the main, taken from this study.

The characteristics of an ESB lead-acid cell designed for load leveling are given in Tables 4-1 and 4-2 and Figure 4-1. This cell has a nominal rating of 12,500 ampere hours to have a end of life capacity of 10,000 ampere hours for a discharge time of 10 hours.

Table 4-1 gives the initial, average and final cell voltages for various discharge times (rates). The ratio of initial to final voltage is approximately 1.2 at the various rates. Therefore, at a constant current for a particular discharge time, the d.c. power output will vary by a factor of 1.2, as is shown in Figure 4-2.

The average energy and power at constant discharge are given in Figure 4-3 (DOD is depth of discharge). Power at constant current as a function of time of discharge is shown in Figure 4-4. Near constant power is only obtained at long discharge times. To have a constant d.c. power output, the discharge current must be increased to compensate for the decrease in cell voltage.

Table 4-1

Performance of VLL-45 Exide Ironclad 12,500 AH Cell

Discharge Rate hrs.	Current Amperes	Cell Voltage			Capacity Ahr	Average Power per cell kW	Energy per cell kWhr	System Energy 5250 cells mWhr	
		Initial volts	Average volts	Final volts					
1	7150	1.730	1.622	1.430	7150	11.6	11.6	60.9	
3	3250	1.912	1.808	1.598	9750	5.9	17.6	92.6	
5	2175	1.928	1.854	1.642	10,875	4.0	20.2	106	
6	1894	1.980	1.874	1.654	11,364	3.6	21.3	112	
7	1690	1.988	1.888	1.660	11,830	3.2	22.3	117	
10	1250	2.016	1.905	1.686	12,500	2.4	23.8	125	
13	1020	2.06	1.95	1.74	13,260	2.0	25.4	136	
Cell Dimensions:		<u>L</u>		<u>W</u>		<u>H<sub>OJ</sub></u>		<u>H<sub>OA</sub></u>	<u>Volume</u>
		<u>in</u>	<u>cm.</u>	<u>in</u>	<u>cm</u>	<u>in</u>	<u>cm</u>	<u>ft<sup>3</sup></u>	<u>m<sup>3</sup></u>
		21.75		21.75		52.31		56.50	15.97
		55.2		55.2		132.9		143.5	.437

Cell Weight: 2250 pounds wet; 1825 pounds dry.

Energy Density: Whr/lb 10.6

10 hr Rate Whr/in<sup>3</sup> .89 (overall); .96 (overjar)

Cycle Life: 250 cycles per year for 10 years at 80% depth.

Table 4-2

Modified Constant Voltage Charges of Cell Type VLL-45

Previous Discharge Output* Ahr and rate	Initial Charge Current Amperes	Charge at Constant I Ahr	Input in Taper Ahr	Charge at Constant I hr	Time in Taper hr	Total hrs	Approximate Constant Wattage per cell KW	Input at Constant W %
10,000 (10 hr)	3000	5625	4375	1.88	3.0	4.9	6.9	56
	2500	6975	3025	2.79	2.8	5.6	5.8	70
	2000	8030	1970	4.02	2.2	6.2	4.6	80
	1500	8815	1185	5.88	1.7	7.6	3.4	88
	1000	9370	630	9.37	1.1	10.5	2.3	94
	500	9745	255	19.49	.5	20.0	1.5	97
9,464 (7 hr)	3000	5089	4375	1.70	3.0	4.7	6.9	54
	2500	6439	3025	2.58	2.8	5.4	5.8	68
	2000	7494	1970	3.75	2.2	6.0	4.6	79
	1500	8279	1185	5.52	1.7	7.2	3.4	87
	1000	8834	630	8.83	1.1	9.9	2.3	93
	500	9204	255	18.42	.5	19.0	1.1	97
8,700 (5 hr)	3000	4325	4375	1.44	3.0	4.4	6.9	50
	2500	5675	3025	2.27	2.8	5.1	5.8	65
	2000	6730	1970	3.37	2.2	5.6	4.6	77
	1500	7515	1185	5.01	1.7	6.7	3.4	86
	1000	8070	630	8.07	1.1	9.2	2.3	93
	500	8445	255	16.89	.5	17.4	1.1	97

\* At 80% of rated capacities ( 10 hr - 12,500Ahr ; 7 hr - 11,830 Ahr: 5hr - 10,875 Ahr)



Figure 4-1

## Lead-Acid Battery Characteristics

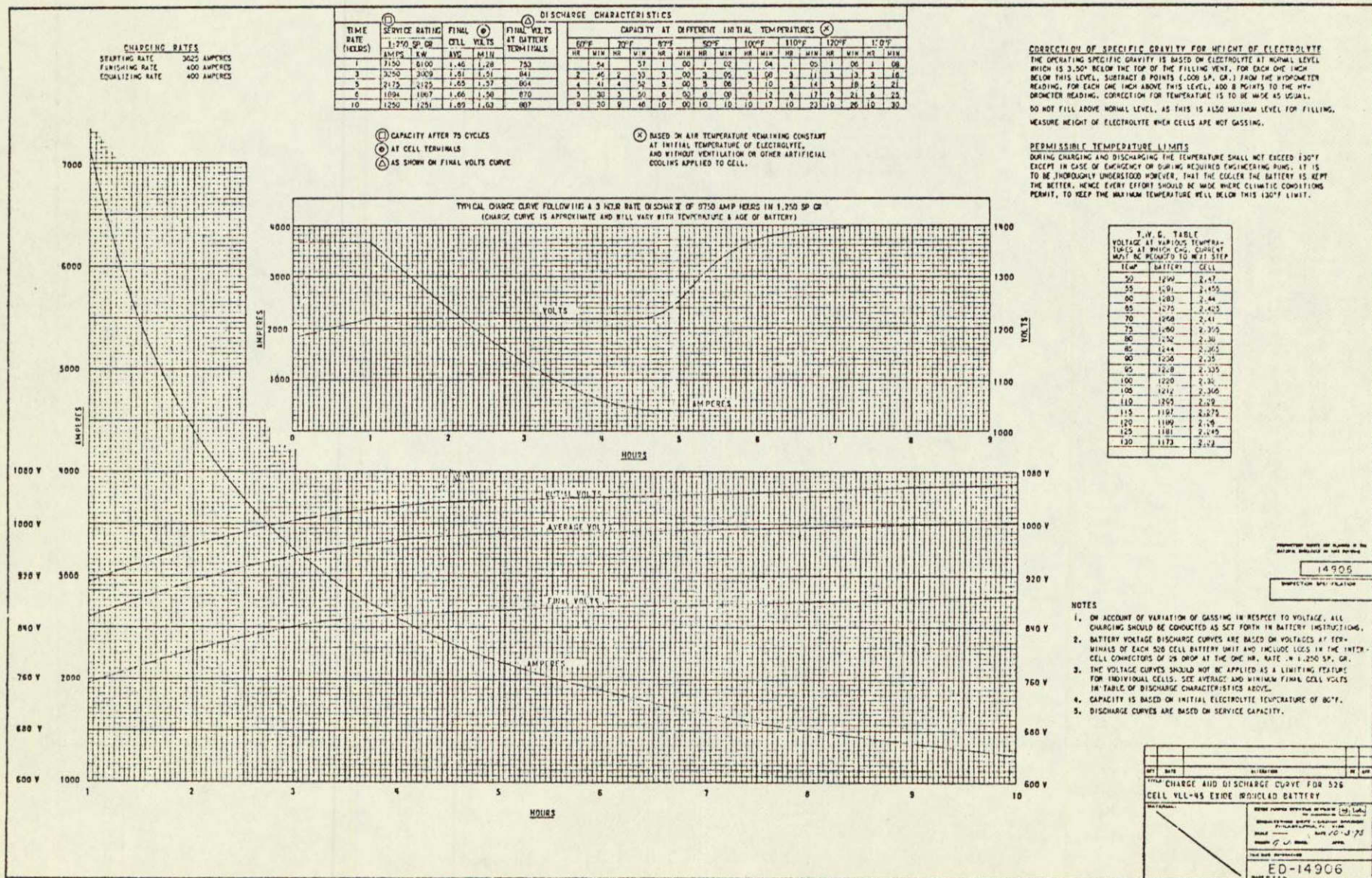




Figure 4-2

VLL-45 Cell Voltage vs. Discharge Capacity, Heat Evolution, and Temperature Rise

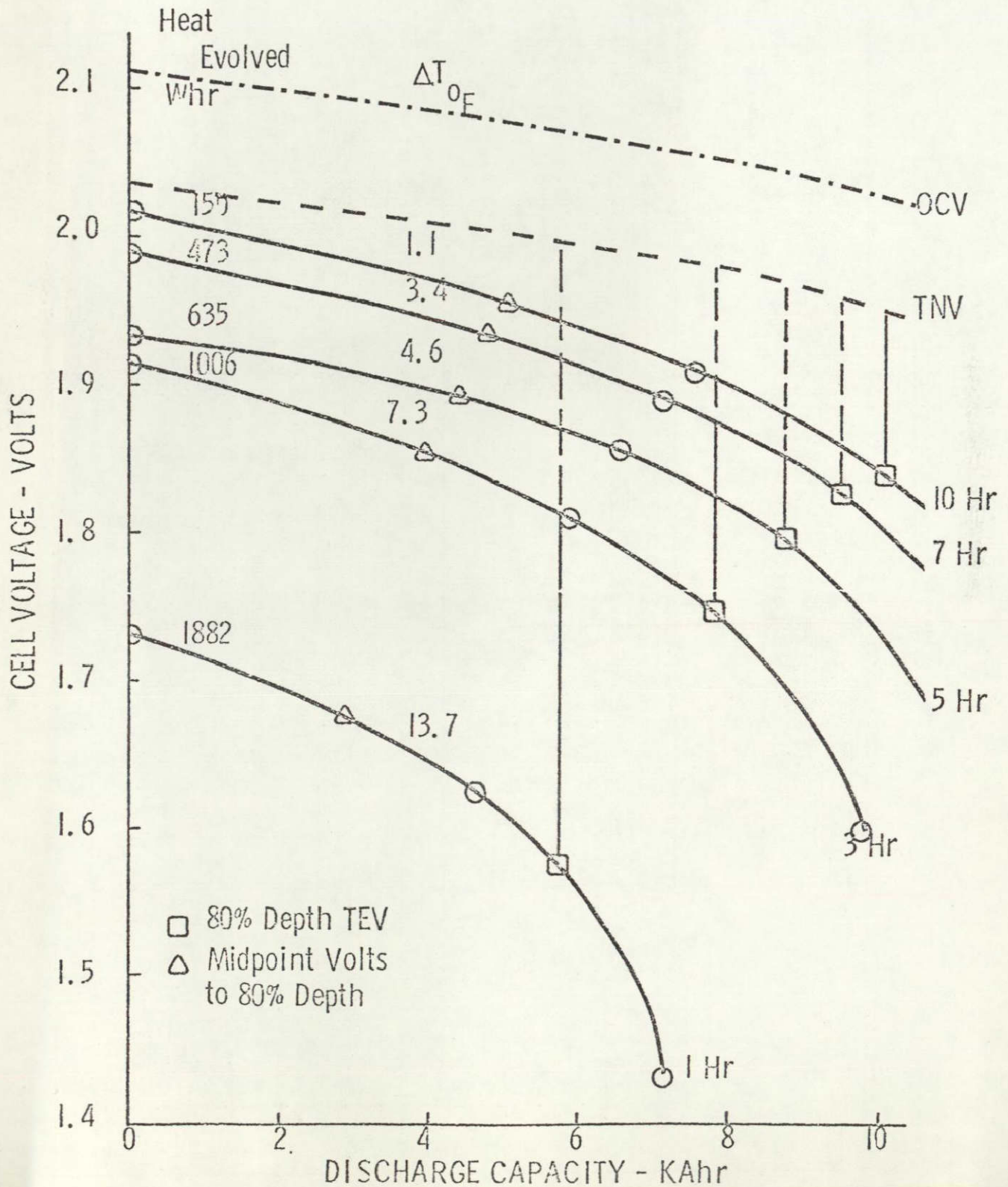
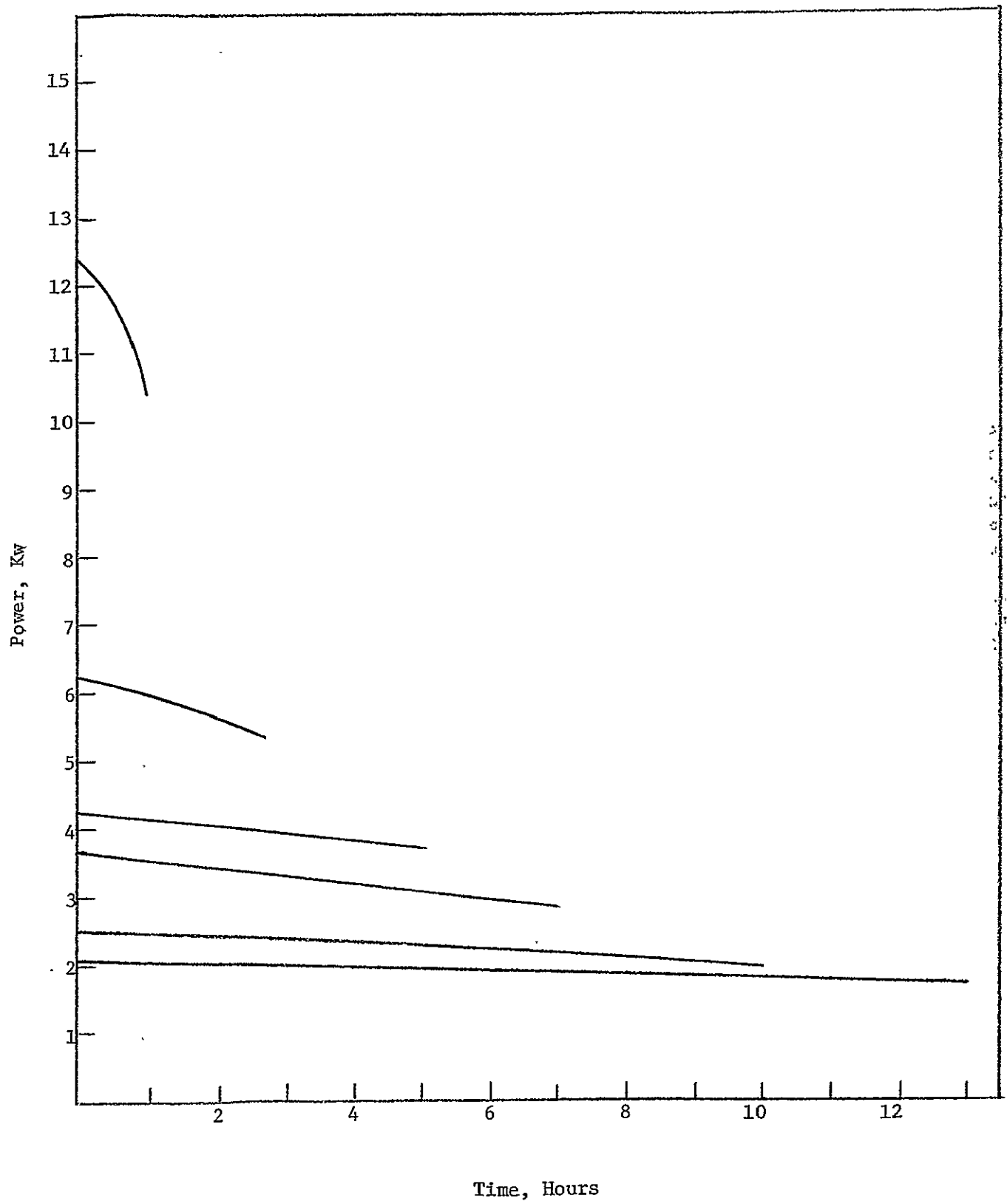


Figure 4-4

Power as a Function of Time of Discharge





This higher current demand, in turn, lowers the cell voltage. Thus, for example, an initial discharge at 1750 amps for 2 hours, followed by 1894 amps for 2 hours, and then 2175 amps for 2 hours will give a near constant output of 3.54 KW for 6 hours. This 25% variation in current will supply a changing current to the inverter and transformer, lowering the efficiency. Further adjustments would have to be made in the current/voltage output of the battery. The iteration will have to be made for a particular installation.

Similarly, constant power charging is possible with long charging times. The charging curves for the ESB load leveling battery are given in Figure 4-5. The higher the initial current, the shorter the time to reach the preset maximum cutoff voltage of 2.32 volts. Beyond this point significant gassing occurs.

The cell charging current vs. time is given in Figure 4-6. While the battery can initially receive high charging currents, after a period of time significant portions of the current are used to produce gas. It is more efficient to reduce, or "taper" the current, to reach the point of the nominal amp-hour capacity. This is normally followed by a low current, in this case, 400 amperes, at higher voltage to finish the charge. A significant portion of this final energy input is used to electrolyze water. This is shown for the nominal 7 hour charge rate in Table 4-3. In this case, 40% of the energy is supplied to the battery in 1.09 hours and it is then tapered for an additional 3.5 hours; 99% of the discharge energy is returned in 3.6 hours. The remaining 2.5 hours are used for finishing. About 9% excess ampere hours and 11% excess power are needed in the finishing process to replace the ampere hours removed in the previous discharge. To reach the 99% point, the input is 23436 KWH and there is an additional 2530 KWH for finishing, for a total of 25966 KWH.

The percentage of input at constant power at various charge rates (not including the finishing current or power) is shown in Table 4-4. It ranges, for this battery, from 50-97% for charge times of 4 to 20 hours.

Figure 4-7 shows the charge input at constant power vs. applied power in kilowatts for the ESB battery. This figure incorporates the constant current portion of Figure 4-6 and the mean charge voltage of Figure 4-5, prior to the taper charge. The charging currents for the 5, 7 and 10 hour rates and the ampere hours returned are:

Charge Rate Hr	Constant Power KW/Cell	Projected Current Amperes	Input, Ahr Output, Ahr
5	3.85	1681	.86
7	2.90	1272	.91
10	2.17	960	.94

Figure 4-5

VLL-45 Cell Charge Voltage vs. Input Capacity

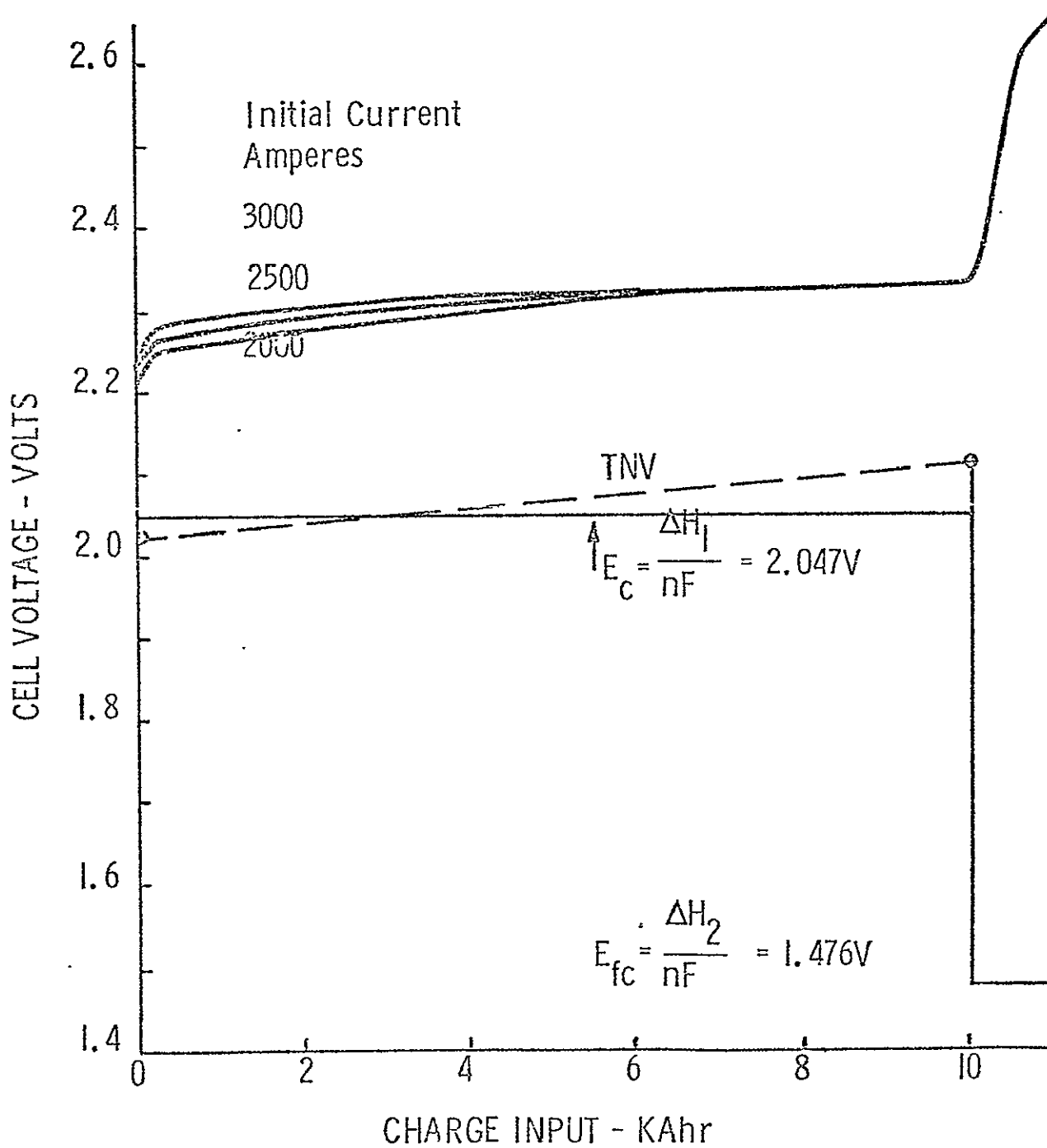


Figure 4-6

VLL-45 Cell Charge Current vs. Time

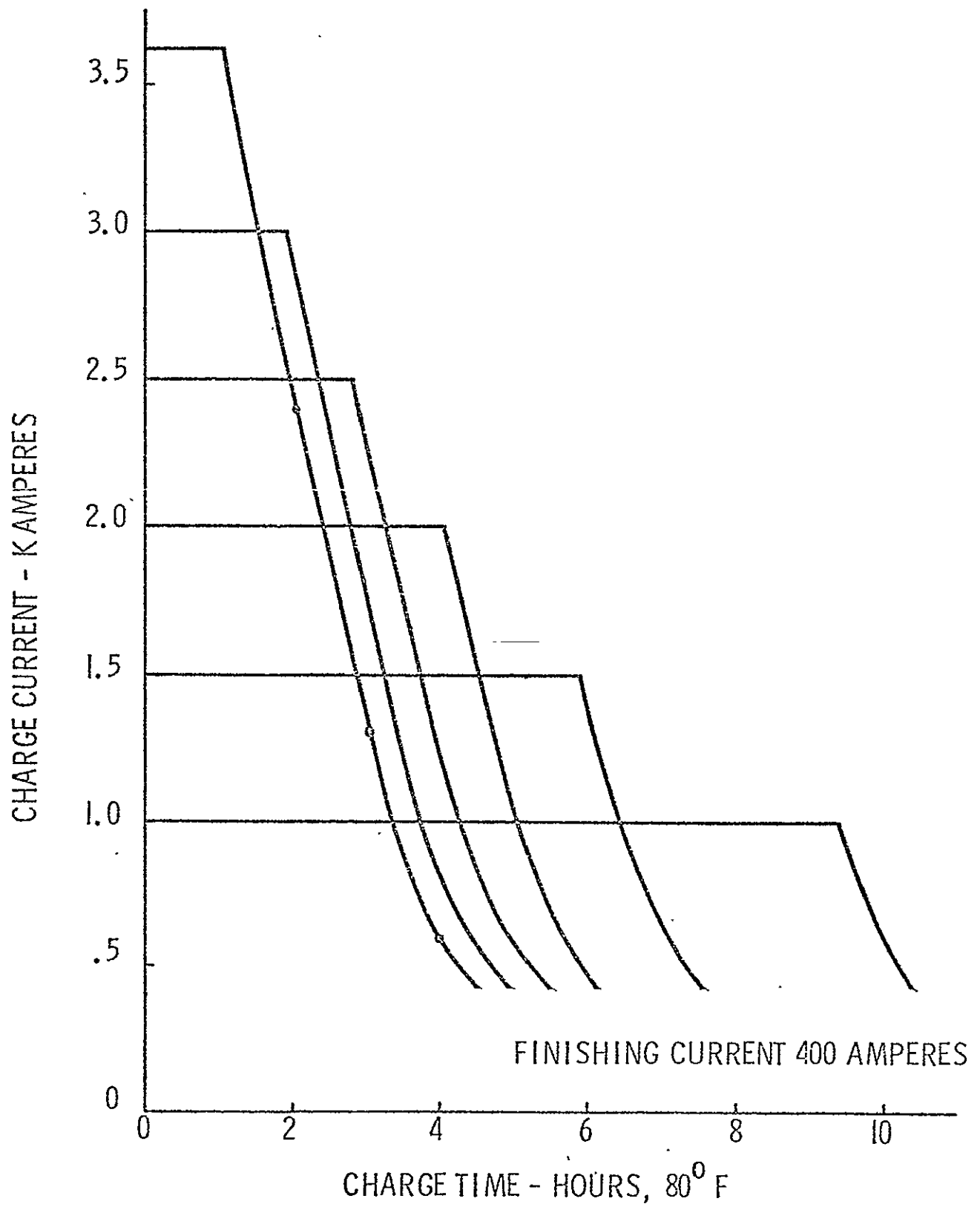


Table 4-3

Heat Evolved on 7-Hour Rate Charge of VLL-45 Cell After 10,000 AH Discharge

<u>Initial or Mean Current Amperes</u>	<u>Charge Time hrs.</u>	<u>Capacity Ahr</u>	<u>Acc. Cap. Ahr</u>	<u>Mean Charge Voltage volts</u>	<u>Mean Thermo- Neutral V volts</u>	<u>MCV- TNV volts</u>	<u>Heat Evolved Q Whr</u>	<u>Acc Heat Evolved Whr.</u>	<u>Acc ΔT (2) °F</u>
3625	1.09	3968	3968	2.29	1.974	.316	1254	1254	9.1
3000	1.00	3000	6968	2.32	2.004	.316	948	2202	16.0
1825	1.00	1825	8793	2.32	2.020	.300	548	2750	20.0
860	1.00	860	9653	2.32	2.030	.290	249	2999	21.8
<u>500</u> (1)	<u>.50</u>	<u>250</u>	<u>9903</u>	<u>2.32</u>	<u>2.032</u>	<u>.288</u>	<u>72</u>	<u>3071</u>	<u>22.3</u>
400	.50	200	10103	2.34	1.755	.59	118	3189	23.1
400	.50	200	10303	2.46	1.476	.98	196	3385	24.6
400	.50	200	10503	2.58	1.476	1.10	220	3605	26.2
400	.50	200	10703	2.62	1.476	1.14	228	3833	27.8
400	<u>.50</u>	200	<u>10903</u>	2.64	1.476	1.16	232	<u>4065</u>	<u>29.5</u>
TOTALS	7.09		10903					4065	29.5

## NOTES:

(1) Finishing current = 400 amperes

$$(2) \Delta T = \frac{Q \times 3.413}{mCp} = \frac{(\text{Whr}) \times 3.413 \text{ BTU/Whr}}{2250 \text{ lbs} \times .209 \text{ BTU/lb}^\circ\text{F}}$$

Table 4-4

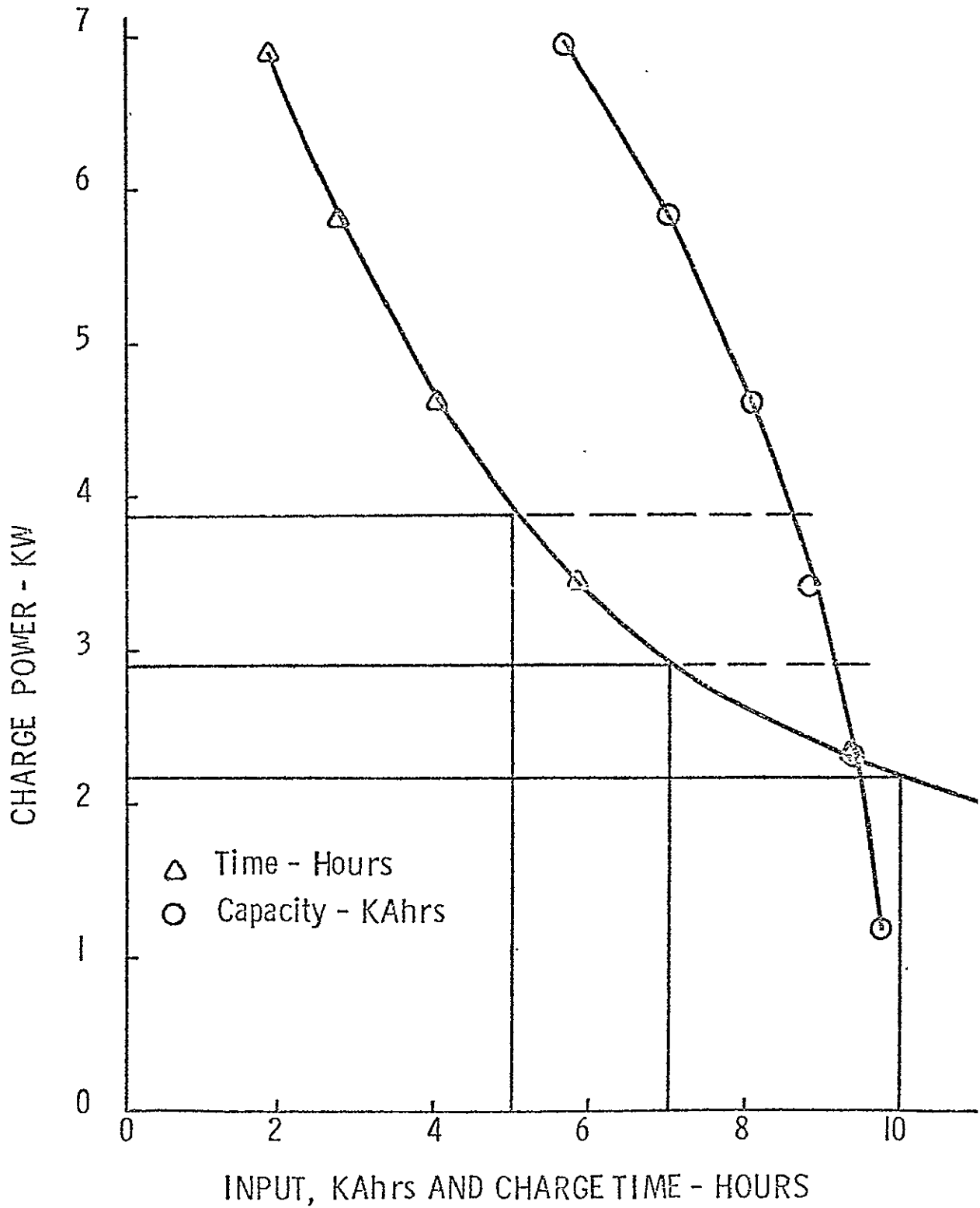
Modified Constant Voltage Charges of Cell Type VLL-45

Previous Discharge Output* Ahr and rate	Initial Charge Current Amperes	Charge at Constant I Ahr	Input in Taper Ahr	Charge at Constant I hr	Time in Taper hr	Total hrs	Approximate Constant Wattage per cell KW	Input at Constant W %
10,000 (10 hr)	3000	5625	4375	1.88	3.0	4.9	6.9	56
	2500	6975	3025	2.79	2.8	5.6	5.8	70
	2000	8030	1970	4.02	2.2	6.2	4.6	80
	1500	8815	1185	5.88	1.7	7.6	3.4	88
	1000	9370	630	9.37	1.1	10.5	2.3	94
	500	9745	255	19.49	.5	20.0	1.5	97
9,464 (7 hr)	3000	5089	4375	1.70	3.0	4.7	6.9	54
	2500	6439	3025	2.58	2.8	5.4	5.8	68
	2000	7494	1970	3.75	2.2	6.0	4.6	79
	1500	8279	1185	5.52	1.7	7.2	3.4	87
	1000	8834	630	8.83	1.1	9.9	2.3	93
	500	9204	255	18.42	.5	19.0	1.1	97
8,700 (5 hr)	3000	4325	4375	1.44	3.0	4.4	6.9	50
	2500	5675	3025	2.27	2.8	5.1	5.8	65
	2000	6730	1970	3.37	2.2	5.6	4.6	77
	1500	7515	1185	5.01	1.7	6.7	3.4	86
	1000	8070	630	8.07	1.1	9.2	2.3	93
	500	8445	255	16.89	.5	17.4	1.1	97

\* At 80% of rated capacities ( 10 hr - 12,500Ahr ; 7 hr - 11,830 Ahr; 5hr - 10,875 Ahr)

Figure 4-7

Charge Power vs. Input  
Capacity and Time to Taper Point



Charging at constant power without tapering the charge current at a preset voltage, limits the input returned to cells and sets the stage for a system failure. Two examples are given below.

Example 1: Five hour discharge-five hour recharge.

Consider charge input, output and residual daily during a weekly routine of 80% depth of discharge cycles during days 1 through 5 and complete recharge on days 6 and 7.

<u>Day</u>	<u>Capacity Input Ahr</u>	<u>Output Ahr</u>	<u>Residual Ahr</u>
1	12,500	8,700	3,800
2	8,550	8,700	3,650
3	8,550	8,700	3,500
4	8,550	8,700	3,350
5	8,550	8,700	3,250
6	8,550	0	11,750
7	750	0	12,500 (or full charge)

The above routine has a good chance of long term success.

Example 2: Seven hour discharge-five hour charge.

Same routine as Example 1 at 80% depth of discharge at 10 hour rate.

<u>Day</u>	<u>Capacity Input Ahr</u>	<u>Output Ahr</u>	<u>Residual Ahr</u>
1	12,500	9,464	3,036
2	8,550	9,464	2,122
3	8,550	9,464	1,208
4	8,550	9,464	294
5	8,550	9,464	(620)
6	8,550	0	7,930
7	4,570	0	12,500

Here, the capacity of the battery will be in arrears before the end of the fifth day and this system will fail because of too little input. Similarly, for other conditions:

<u>Constant Power Charge, Hours</u>	<u>Discharge Rate, Hours</u>
	4 5 7 10 13
5	+ + - - -
7	+ + + - -
10	+ + + + -

In general, charge time must exceed discharge time for constant power input.

C&D Batteries Division of Electra Company performed an analysis of load leveling batteries for the International Lead Zinc Research Organization. This analysis while not as detailed, gives essentially the same charging conditions as the ESB study. Specifically, a charge at constant power for 7 hours for 75-80% of capacity, followed by a constant voltage charge at 2.45 volts per cell for 3-4 hours, was defined. Thus the lead-acid industry reports indicate that constant power charging (and discharging) is possible only if very long operating times are used.

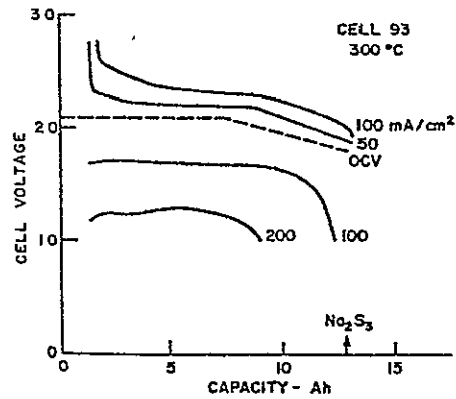
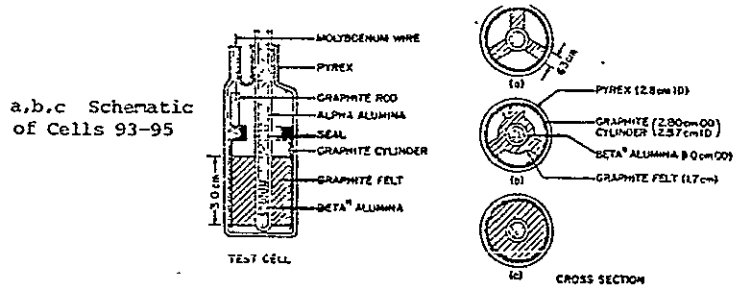
The charge/discharge characteristics of the other battery systems under consideration for load leveling are not as well defined as those of the lead-acid system. But those batteries using solid reactants for anode and cathodes will generally have sloping charge and discharge curves at a given current, due to changes in concentration and activities. For example, the characteristics of a sodium-sulfur cell from Ford (2) are shown in Figure 4-8 and 4-9. The change of characteristics are greater than those of a lead-acid battery. The swing of voltage at constant current, in this case, exceeds that of the lead-acid battery.

Battery systems which have more fuel cell-type characteristics, with renewable reactant supply and product removal, such as zinc-chlorine, lithium-chlorine, zinc-air, and redox, will have a markedly more constant voltage at constant current charge or discharge. The above problems will be markedly less with these systems.

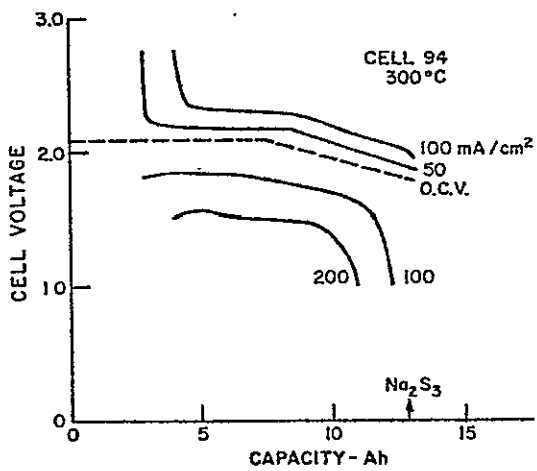


Figure 4-8

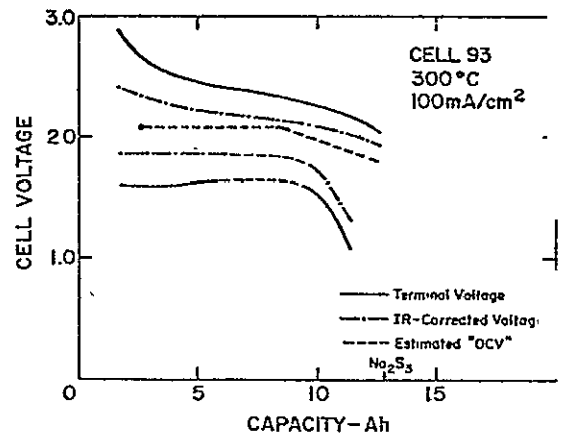
Sodium-Sulfur Battery Characteristics



Charge/Discharge Characteristics of Cell 93



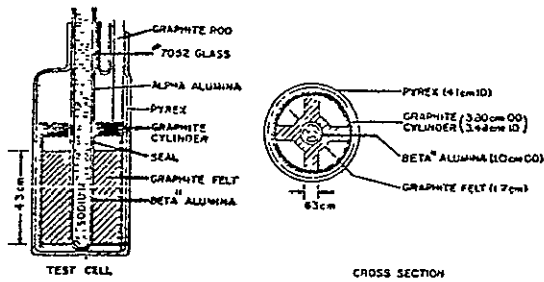
Charge/Discharge Characteristics of Cell 94



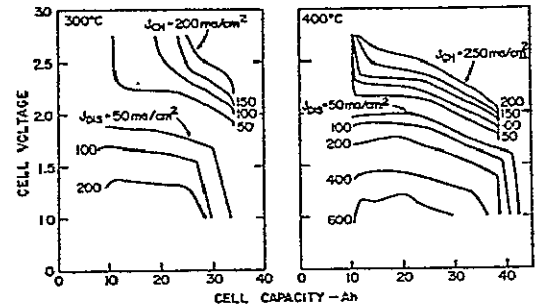
Charge/Discharge Characteristics of Cell 93 - IR Corrected

Figure 4-9

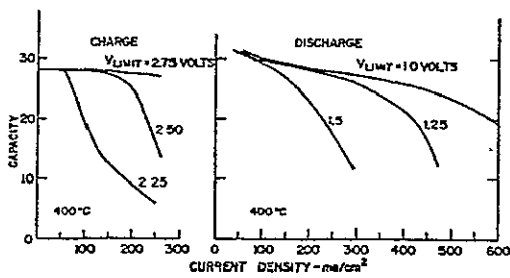
Additional Characteristics of  
Sodium-Sulfur Batteries



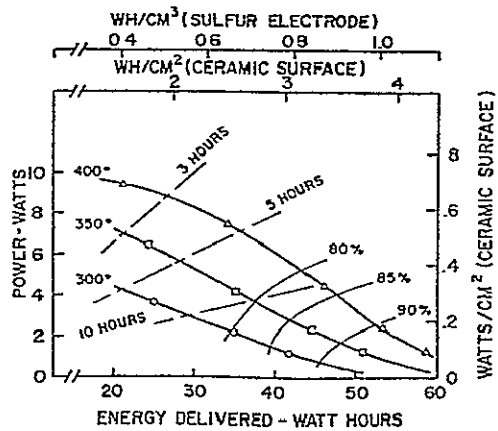
Schematic of Cell 89



Charge/Discharge Characteristics of Cell 89



Effect of Cell Voltage Limits on Cell 89



Performance  
Characteristics of  
Cell 89

REFERENCES

1. Doe, J., "Design and Cost Study for State of Art Load Leveling Batteries, April 1975 - Sept. 1975," EPRI Contract RP419-1.
2. Weiner, S., "Sodium Sulfur Battery," Symposium on Energy Storage Electrochemical Society Meeting, Dallas, Texas 1975.

## 5. POWER CONDITIONING

Battery energy storage systems for utility applications must interface with the ac power lines and with ac/dc power conditioning equipment. This interface puts a great burden on both the battery system and on the power conditioning system. The utility must have good quality ac power with good power factor, limited injection of harmonics, compatible voltage and frequency tolerances. The dc power source must have power supplied or withdrawn at the appropriate voltage range and the ripple in voltage and current must be low. In addition, the power conditioning equipment must be able to survive load line and/or generation faults in the ac network and be able to clear dc faults (preferably without on-site action or maintenance to restore service).

The ac/dc power conditioning for dc energy storage/production systems on the megawatt scale has been studied in detail by Westinghouse under an EPRI contract. They considered battery, fuel cell, MHD and superconducting magnetic energy storage system requirements.

For the battery source, this study only considered a hypothetical battery, with the following characteristics:

Charge cut-off voltage - 1700 volts

Voltage at commencement of charge or discharge - 1300 volts

Discharge cut-off voltage - 1000 volts

Hence: Charging voltage ratio 1.3:1

Discharge voltage ratio 1.3:1

Total voltage ratio 1.7:1

The internal battery resistance was assumed to be zero for transient analysis. A charge time of 7 hours and a discharge time of 10 hours was assumed. While this is a hypothetical battery, it has the properties of a lead-acid system.

An analyses was made of eight different types of inverter/converter systems. These are listed in Table 5-1, together with the costs (\$/KW) on a discharge-limited design point. In the battery system, the highest current occurs at the discharge cut-off and since inverters are current limit-rated, this is a design point. The cost of the power conditioning equipment is also a strong function of voltage level. Westinghouse analyzed various systems as a function of voltage. These are shown in Figures 5-1 to 5.5 (VSF refers to voltage safety factor.)

Table 5-1

Specific Costs of Candidate System Preliminary Designs

<u>Source</u>	<u>System</u>							
	<u>CFLCI</u>	<u>BBLCI</u>	<u>CMLCI</u>	<u>CHLCI</u>	<u>VFLCI</u>	<u>PAFCI</u>	<u>CAFCI</u>	<u>HF LINK</u>
Battery	70.9	73.6	67.6	77.7	74.6	77.3	77.1	70.5

CFLCI = Current-fed, naturally commutated inverter.

BBLCI = Buck-boost current-fed naturally commutated inverter.

CMLCI = Complementary current-fed inverters.

CHLCI = Chopper-current-fed naturally commutated inverter.

VFLCI = Voltage-fed naturally commutated inverter.

PAFCI = PAC voltage-fed force-commutated inverter.

CAFCI = CAC     "     "     "

HF LINK = High frequency link.

PAC = Phase angle controlled.

CAC = Conductance angle controlle

N.B. Costs in \$/KW rating.

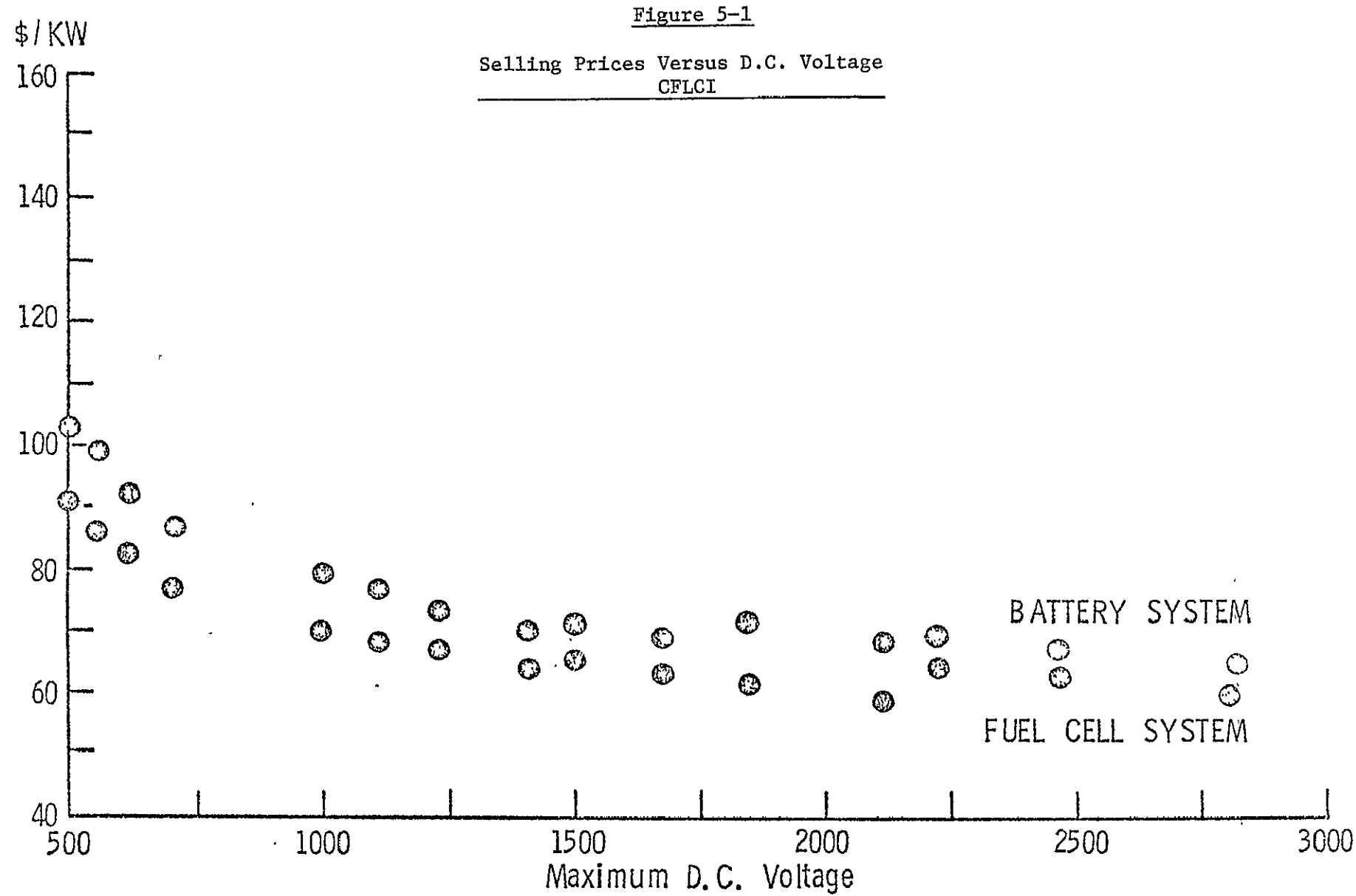


Figure 5-2

Selling Prices Versus D.C. Voltage  
CAFCI, 1.4 V.S.F.

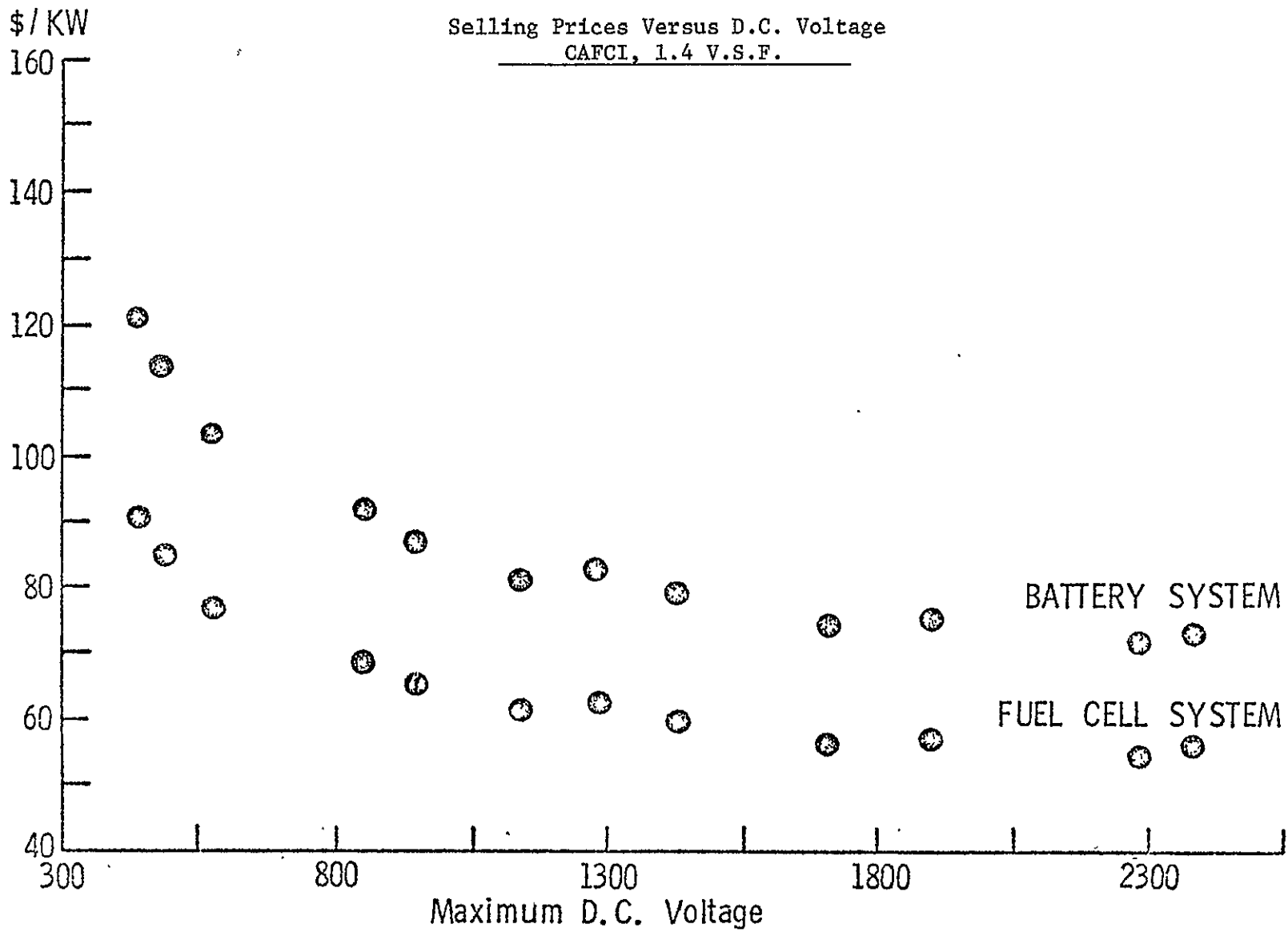


Figure 5-3

Selling Prices Versus D.C. Voltage  
CAFCI, 2.0 V.S.F.

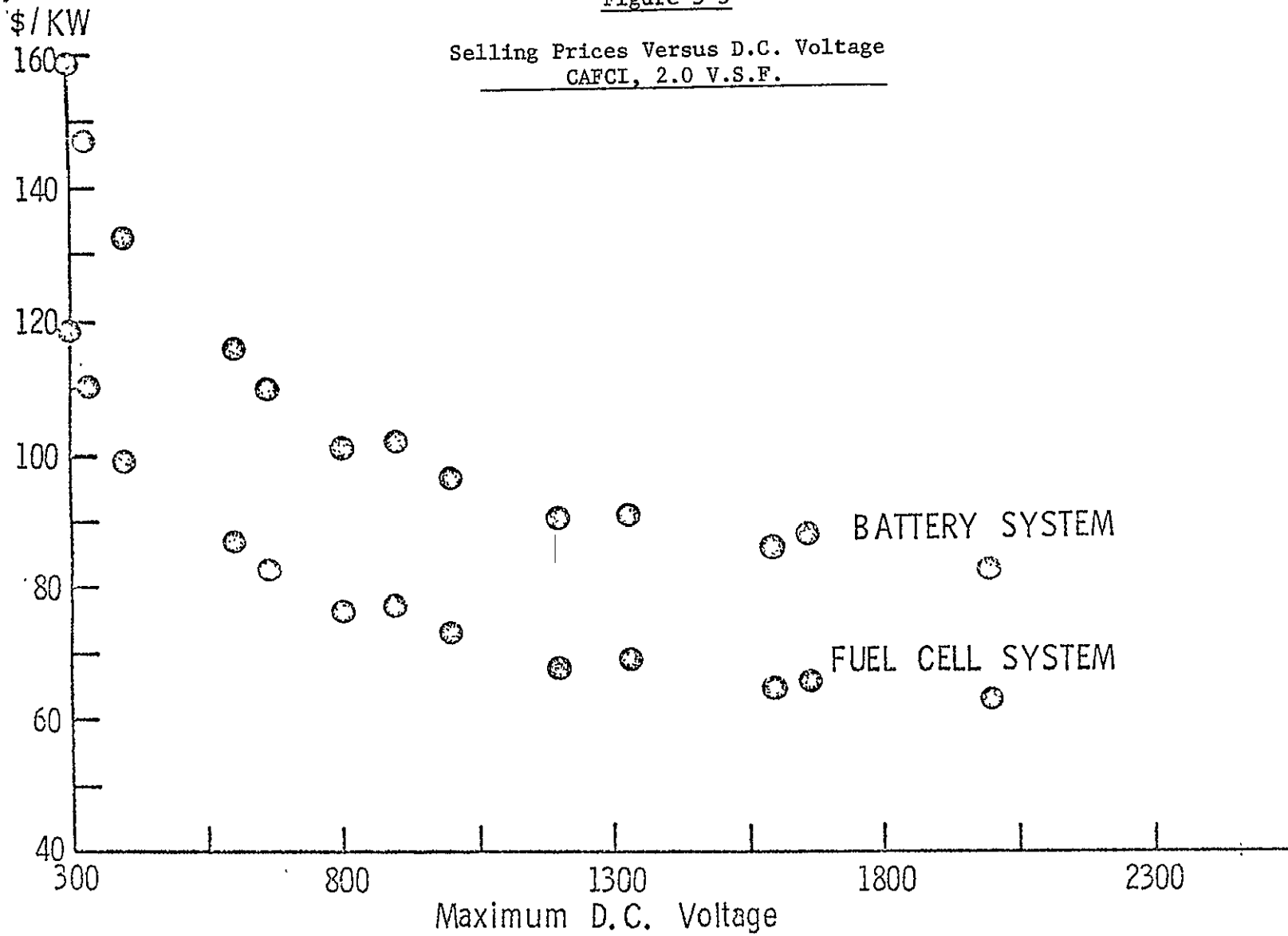




Figure 5-4

Selling Prices Versus D.C. Voltage  
HF Link, 1.4 V.S.F.

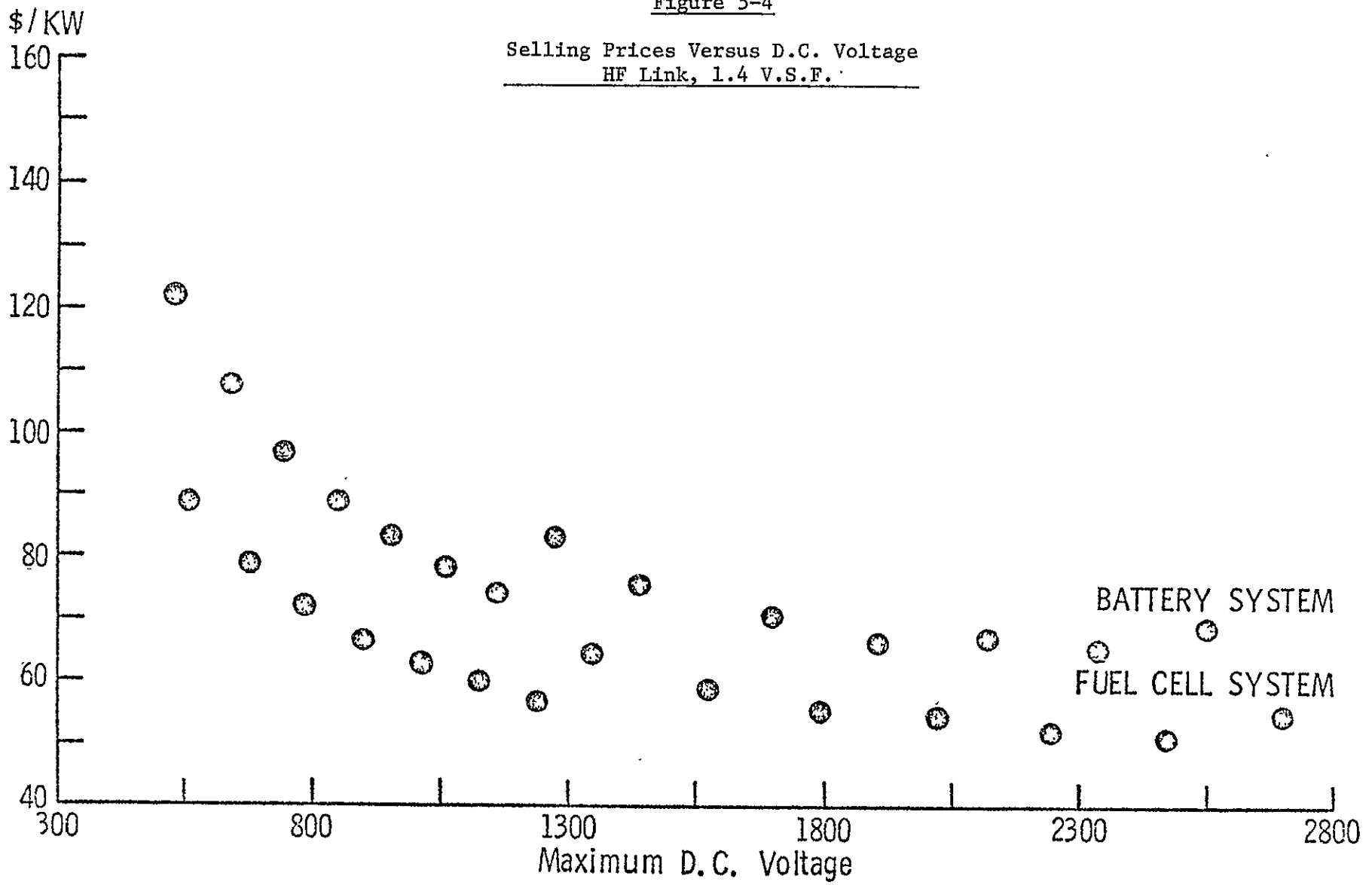
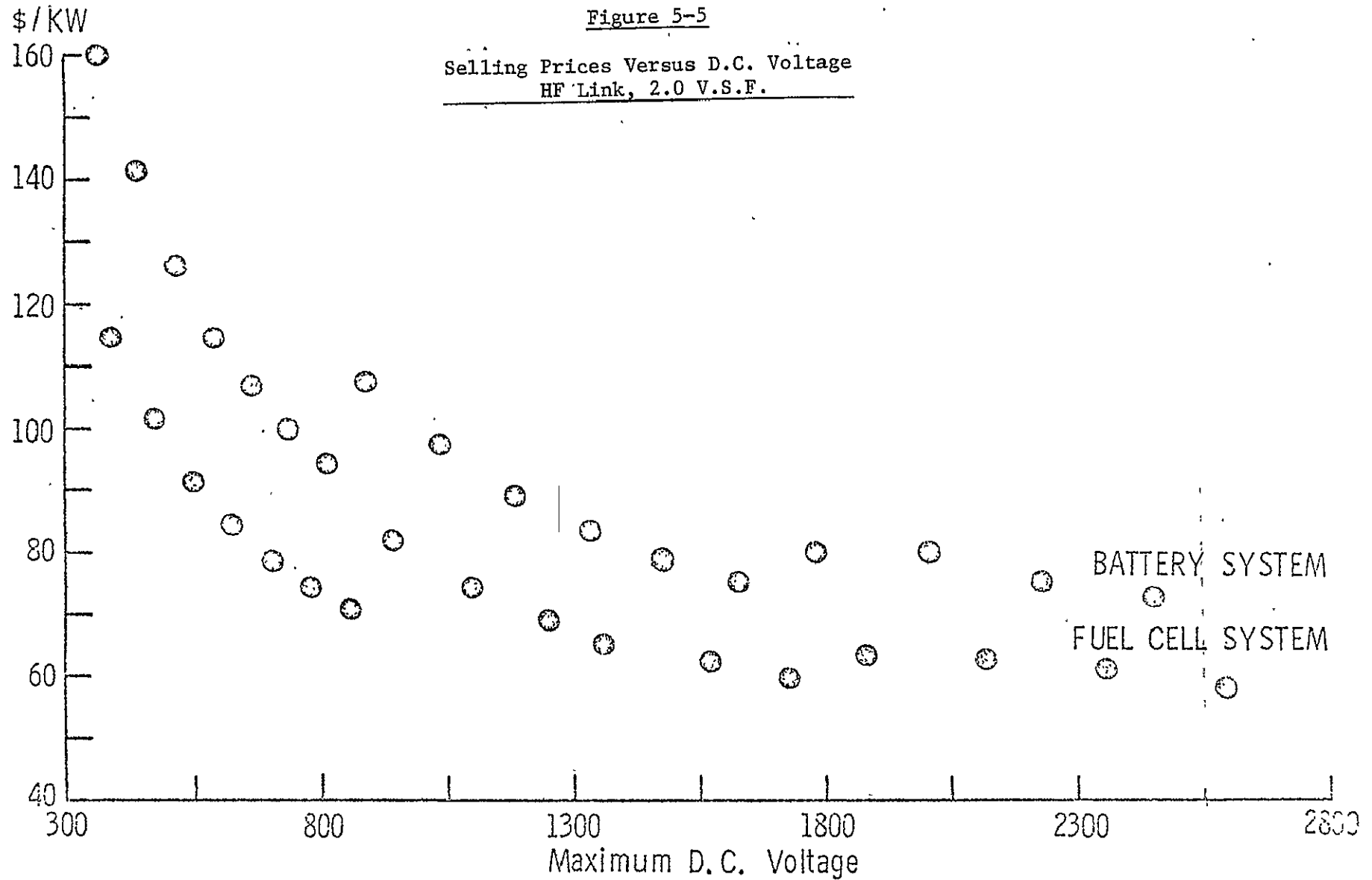


Figure 5-5

Selling Prices Versus D.C. Voltage  
HF Link, 2.0 V.S.F.



A distinct knee in the costs occurs in the voltage region of 800-1000 volts. While there are lower costs at higher voltages, these are not major reductions. Voltages above 1500-2000 v. are probably not attractive. It is also evident that battery voltages below 500 v. make for a costly system of power conditioning. The VSF has a distinct effect on costs and it must be determined with further research and development on the high technology power conditioning systems.

The cost of the various inverter systems is broken down into cost of the various component structures as a function of total cost. In Table 5-2 it is evident that the cost is not centered in any one item. The most significant cost item (except in the very high technology and least developed inverter) are the transformers. Efforts in reducing transformer costs would be rewarding.

The transformers in the power conditioning are considerably different than the standard design for the utility station or substation transformers. The designs incorporate features used for arc furnace transformers-special insulation and internal bracing to handle the magnetically induced stresses. In addition, the flux densities will probably be 15% less to accommodate harmonics. These factors considerably affect the cost of power conditioning compared to conventional utility transformers.

Quoting from the Westinghouse report, "The costs assigned to 'Inverters' in Table 5-2 are in reality the costs for all active devices in the power processing switching matrices, plus their inseparable ancillaries (heat sinks, snubbers, gate drives, control, cooling systems, etc.). These costs range from 20% of total for the 'lowest technology' approach to over 40% for the HF link, the 'highest technology' scheme. Thus, the commonly held opinion that higher technology approaches will benefit substantially as regards their cost, from future device developments (particularly in the more sophisticated fast switching thyristors) seems warranted. However, some caution must be exercised in making this type of prediction. To emphasize this, the costs associated with the devices alone are displayed separately as a line item-devices. It can be seen that these represent only about 40% of the 'Inverter' costs and from 8% (low technology, CFLCI) to 18% of total system cost. Thus any hopes for dramatic system cost improvements as a result of future reductions in semiconductor prices seem, to us, to be ill-founded. In addition, in assessing the potential benefit of device parameter improvements, we must remember the substantial portion of the equipment cost associated with ancillaries. This indicates that a reduction in the number of devices used, through increase in voltage and/or current ratings, is likely to be just as important a factor, if not more so, as improvement in switching characteristics when it comes to reducing system costs. Taking into account normal market pressures and the historical pattern of device development, it would seem that the schemes using relatively slow, high voltage and high current devices stand perhaps more chance of reaping future economic benefits from device developments than those systems employing 'inverter type' thyristors. This scenario could be changed, of course, by massive infusion of development funds into fast switching thyristor R and D."

Table 5-2

Inverter Cost Breakdown

	<u>Price Structure Percentage</u>				
	<u>CFLCI</u>	<u>CMLCI</u>	<u>PAFCI</u>	<u>CAFCI</u>	<u>HF</u>
Transformers	34.3	20.6	34.1	21.0	7.9
HF Link					8.0
Filters	1.6	1.1	1.1	1.1	0.9
Power factor correction	8.5	1.3			
Switch gear	13.6	15.0	0.9	0.9	16.1
High speed DC interruption	14.0	14.6			13.9
Interphase transformers			5.7	5.0	
Reactors					7.0
DC reactors	10.9	10.1			9.6
Commutation components		9.0		25.1	
Input capacitors			5.9	10.4	
Inverters*	<u>17.2</u>	<u>27.4</u>	<u>34.4</u>	<u>36.5</u>	<u>36.6</u>
	100	100	100	100	100
* Devices	7.0	10.8	17.5	17.8	17.5

The electrical switch gear is a significant item in power conditioning cost. It was Westinghouse's opinion that the reconfiguration of the battery strings within the battery storage source when transferring from charge to discharge mode, or during various points in a charge or discharge sequence, was not economically attractive. This could put an intolerable demand on the batteries.

It was assumed, in all cases studied by Westinghouse, that the charging of batteries would be at constant power over most of the charging period. The discharge power would never exceed the conversion equipment discharge rating, but the discharge power could vary over a complex load leveling profile within this rating. It was Westinghouse's opinion that batteries which demand complex charging power profiles would not be viable energy storage media. It could be, however, in the final analysis, that power conditioning schemes and rigid bus-bar and switchgear systems that cannot accommodate to battery power profiles are themselves not viable in energy storage-network interfaces.

The analysis by Westinghouse indicated that there was no cost advantage for modularizing the power conditioning. That is, to have the power conditioning system made up of a number of inverters connected to a number of batteries; and to have the output collectively supplied to the ac network.

A very important factor in any power conditioning scheme is the efficiency loss associated with the ac/dc conversion and the dc/ac inversion. Westinghouse evaluated the various loss factors for the candidate inverters. They are given in Figure 5-6 and Table 5-3. The breakdown of losses among the various subcomponents is given in Table 5-4. The losses are in the range of 5 to 6% at full load for the common inverter scheme and higher for other approaches. The losses are about equally divided between the transformers and the active conversion devices. These are areas for active research and development. A 5% loss on charge or discharge is equivalent to a 100 millivolts difference in the charge and discharge voltage of a lead-acid battery. This is significant.

Westinghouse recommended the current-fed, naturally-commutated inverter for the short-term but could not find a clear-cut long-term solution. The charging and discharge characteristics of batteries did not fit well with Westinghouse equipment designs and costing procedures -- a difficult problem for the power conditioning system. There is a great need for further clarification of the battery/power conditioning interface and trade-off studies.

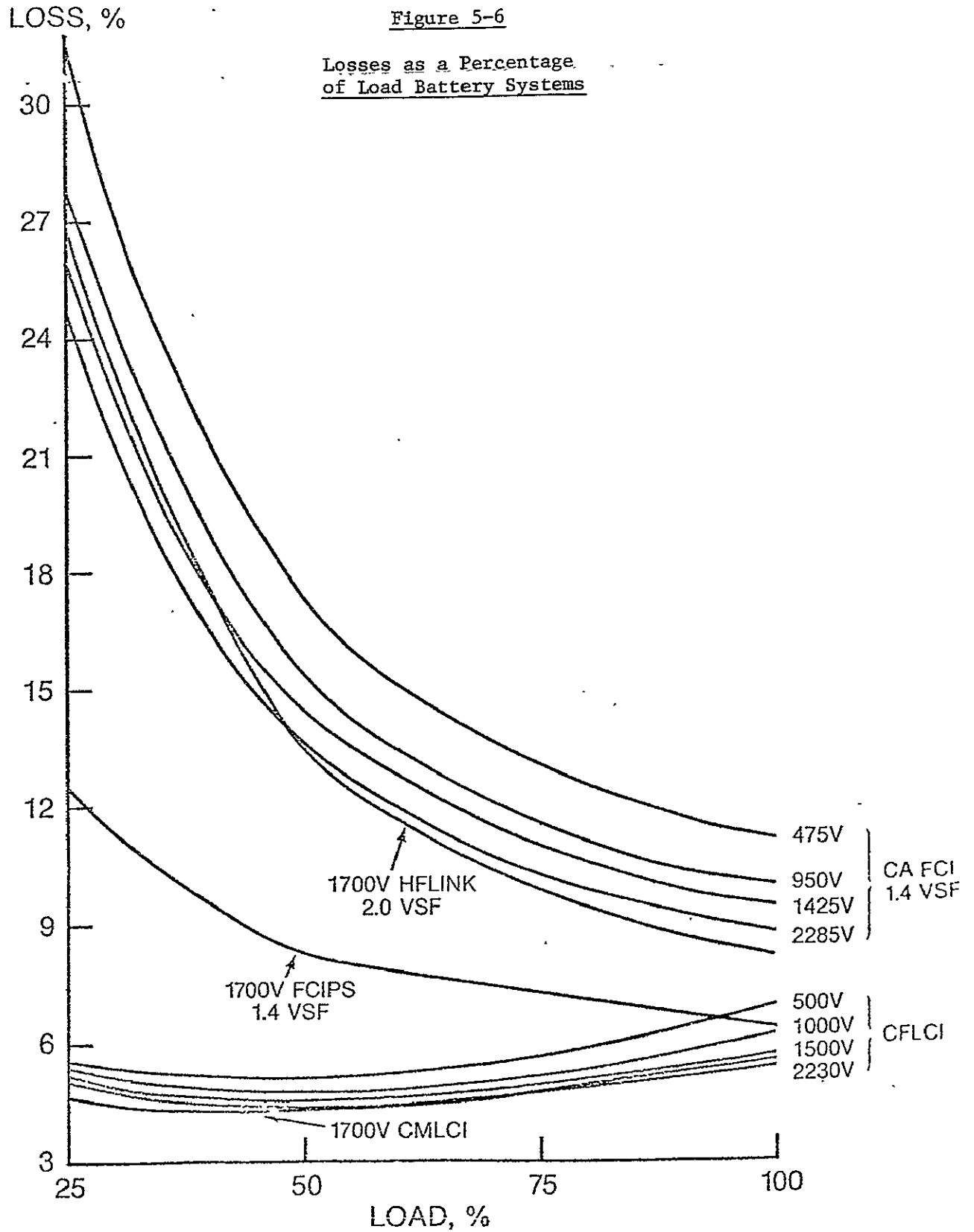


Table 5-3

Losses of Preliminary Designs

(At Full Load, As % of Power Throughput)

<u>Inverter Scheme</u>					
<u>Source</u>	<u>CFLCI</u>	<u>CMLCI</u>	<u>HF Link</u>	<u>PAFCI</u>	<u>CAFCI</u>
Battery	5.53	5.34	10.2	6.35	7.04

Table 5-4

Distribution of Losses Among Inverter Components

<u>Circuit Element</u>	<u>Loss Structure</u> (% loss in major components)				
	<u>CFLCI</u>	<u>CMLCI</u>	<u>PAFCI</u>	<u>CAFCI</u>	<u>HF Link</u>
Transformers	2.80	1.57	3.13	1.86	1.57
Filters and Power Factor Correction	0.51	0.24	0.28	0.26	3.35
DC Reactors	0.80	0.81			0.71
Commutating Circuit		0.52			
Input Capacitors			0.07	0.12	
Interphase Reactors			0.34	0.25	
Other Reactors					0.92
Active Devices and Coolers	1.43	2.20	1.90	2.63	3.62

## 6. ENVIRONMENTAL IMPACT AND SAFETY CONSIDERATIONS

The environmental and safety considerations of the serious battery candidates for energy storage systems present no particular problems. Bechtel (1) has prepared a preliminary environmental and safety assessment for the battery energy storage test facility (BEST) under a contract to Argonne National Laboratory. The format of the report closely follows that of an environmental impact statement for EPA. The battery systems actually considered include:

- Lead-acid
- Zinc-halogen
- Lithium and sodium high temperature systems

They conclude that there was no environmental or safety problem if standard practices and codes were followed. The major concern was the release of toxic gases or corrosive smoke from an upset. The possibilities of an upset can be reduced if great care is used in the mechanical activities at the battery site and in regular inspection procedures.

In particular, a caustic wash or silica gel trap was recommended for chlorine leaks and an inert argon atmosphere for the alkali metal battery rooms. Thus, plus adherence to OSHA and other codes, should provide adequate safety and environmental considerations.



References

Scientific Development, Bechtel Corporation, Argonne National  
Laboratory Contract No. 31-109-38-2962, September 1974.

**EXXON** RESEARCH AND ENGINEERING COMPANY  
GOVERNMENT RESEARCH LABORATORIES

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REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

Task IIIA

Documentation for Stage 1  
Model Computer Program

By

Exxon Research and Engineering Company  
Government Research Laboratories  
1900 East Linden Avenue  
Linden, New Jersey 07036

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G. Ciprios

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NASA-Lewis Research Center  
Cleveland, Ohio 44135

June 23, 1976

**government  
research**

## Table of Contents

Input Description .....	1
Input Format	
Card Structure	
Base Case Data	
Parametric Case Data	
Case Delimiter Card	
Error Handling	
Card Input Instructions .....	5
Program Structure .....	57
Overall Structure	
Input Phase	
Electrochemical Calculation Phase	
Economic Calculation Phase	
Output Phase	
Subroutine Descriptions .....	59
APPENDIX 1 - Outline of Computational Procedures Used in Stage 1 Model of Redox Energy Storage Systems .....	1-1

Storage Battery Program ( Model 1 )

Program Documentation

June 1976

## Input Description

### Input Format

The input to the Storage Battery Program( Model 1 ) consists of a series of cases. A case consists of a base case and any number of parametric cases.

#### Base Case

A base case consists of all the input data required by the program to do the calculations.

#### Parametric Case

A parametric case contains only that information that differs from the base case. The changes indicated by parametric cases are accumulative such that parametric case number four, say, modifies parametric case number three and not the base case. In other words, the user must reset all data to base case conditions, if so desired, because the program will not.

### Card Structure

Each input card consists of eight fields of ten columns each. The first field contains an unique keyword which describes the data on the card. Depending on the keyword, the remaining data on the card will be in the next one to seven fields.

## Keywords

The allowable keywords are:

CELL	HTCAPACITY
CELLCOST	MEMBRANE
CELLDENSTY	MOLEWEIGHT
CELLSIZE	POWER
CHARGE	POWERCOND
CHRGFLOW	REACCONC
DENSITY	SOLNCOST
DHRGFLOW	STACKSIZE
DISCHARGE	TEMP
EFFICIENCY	TRALRCOST
ELECCONC	TRALRSIZE
ELECTRANS	ULLAGE
*END	
*PARA	
*TITLE	

## Base Case Data

The program sets all input variables to zero before each base case. Therefore, any input variable that is not specified will have the value of 0.0.

## Parametric Case Data

The user need supply only that data which differs from the previous case { base case or parametric } because the program only updates the non-zero entries on a card. If no data on a certain keyword card changes then the user need not supply that card. Also, if the user wants to zero out a number he must enter a suitably small number, e.g. 0.0001, because the program cannot distinguish between a blank field, which it sets to 0.0, and a valid 0.0 entry.

## Case Delimiter Cards

The user indicates that the data is complete for one set of calculations by supplying either a \*END or a \*PARA card after the data.

### \*END Card

A \*END card indicates that the preceding data is complete and denotes the end of a case. Therefore, upon returning to the input phase, the program will recognize the next cards as a new base case and will re-initialize all input variables to zero.

### \*PARA Card

A \*PARA card indicates that the preceding data is complete and that additional parametric cases will follow. Therefore, upon returning to the input phase, the program will process the following cards as a parametric case and only change the non-zero data values that are entered.

## Error Handling

The program tries to anticipate common input errors and take the appropriate action before proceeding further.

### Input Processing

A misspelled keyword renders the rest of that case's data useless; but rather than flush the input cards to the first \*END card (new base case) the program will continue to process the input data looking for more possible errors. In this way, most errors can be found at once rather than one at a time.

Also, the program checks for those variables and variable combinations that are used as divisors in the electro-chemical equations to insure that a zero divisor does not result. If so, these variables are printed out and the program remains in the input phase until that condition no longer exists or a \*END card is read.

### Calculation Phase

In the electro-chemical calculations the program constantly checks for those variables or variable combinations that would result in a zero divisor. If any are detected, the program prints out the expression for the user's information and returns to the input phase.



### Card Input Instructions

The next pages describe the input forms and how to fill them out. An example form will be on the facing page as an easy reference for the user. The input cards are described in alphabetical order to provide the user with a convenient reference tool. The user should be reminded that the input cards can be submitted in any order with only two exceptions ( Case Delimiter and Title Cards)

As a programming aid, the FORTRAN variable name used in the program is listed with each variable description along with the column numbers of its field on the card.

CELL CARD

										CELL VOLTAGE (volts)										NUMBER OF PARALLEL CELLS										REACTANT · UTILIZATION FACTOR																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL																																																																															

# Cell Card

Cell Voltage ( VR )  
cc. 11-20

Enter the assumed  
time-averaged reversible cell  
voltage.  
( volts )

Parallel Cells ( NP )  
cc. 21-30

Enter the number of parallel  
cells.  
( - )

Reactant Utilization Factor ( U )  
cc. 31-40

Enter the reactant utilization  
factor U, where:

$$u = \frac{\text{total moles involved}}{\text{total moles present}}$$

( - )

CELL COST CARD

										PLASTIC (\$/kg)										CURRENT COLLECTOR (\$/kg)										ELECTRODE DEPOSIT (\$/kg)										MEMBRANE (\$/m <sup>2</sup> )										STACK FACTOR																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
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Cell Cost Card

Plastic Cost { CCP }  
cc. 11-20

Enter the cost of the cell  
plastic.  
( \$/kg )

Collector Cost { CCC }  
cc. 21-30

Enter the cost of the current  
collector material.  
( \$/kg )

Electrode Cost { CE }  
cc. 31-40

Enter the cost of the  
electrode deposit.  
( \$/kg )

Membrane Cost { CM }  
cc. 41-50

Enter the cost of the membrane  
material.  
( \$/kg )

Stack Factor { FM }  
cc. 51-60

Enter the ratio of the stack  
manufactured cost to the stack  
materials cost. Normal range  
is probably in the  
neighborhood of 2-3.  
( - )

CELL DENSITY CARD

										PLASTIC (gm/cm <sup>3</sup> )										CURRENT COLLECTOR (gm/cm <sup>3</sup> )										ELECTRODE DEPOSIT (gm/cm <sup>3</sup> )																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL DENSITY																																																																															

Cell Density Card

Cell Plastic Density ( RHOCP )  
cc. 11-20

Enter the density of the cell  
plastic material used in the  
cell.  
( gm/cm<sup>3</sup> )

Current Collector Density ( RHOCC )  
cc. 21-30

Enter the density of the  
current collector material.  
( gm/cm<sup>3</sup> )

Electrode Deposit Density ( RHOE )  
cc. 31-40

Enter the apparent bulk  
density of the electrode  
deposit.  
( gm/cm<sup>3</sup> )

CELL SIZE CARD

										ELECTRODE THICKNESS (cm)	FLOW CHANNEL THICKNESS (cm)										CURRENT COLLECTOR THICKNESS (cm)										END PLATE CONDUCTOR THICKNESS (cm)																																																
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL SIZE																																																																															



Cell Size Card

Electrode Thickness ( EE )  
cc. 11-20

Enter the electrode thickness.  
( cm )

Flow Channel Thickness ( TAU )  
cc. 21-30

Enter the thickness of the  
flow channel. It is the same  
for each reactant.  
( cm )

Current Collector Thickness ( GAMMAC )  
cc. 31-40

Enter the thickness of the  
current collector for the  
interior portion of the cell.  
( cm. )

End Plate Conductor Thickness ( GAMMAE )  
cc. 41-50

Enter the thickness of the  
conductor on each end plate.  
( cm. )

# CHARGE CARD

										CURRENT DENSITY (amp/cm <sup>2</sup> )										NON-OHMIC CELL POLARIZATION										CONVERTER CHARGING VOLTAGE (volts)																																																	
																				INTERCEPT										SLOPE																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CHARGE																																																																															

Charge Card

Current Density ( IC )  
cc. 11-20

Enter the cell current density  
during charge.  
( amp/cm<sup>2</sup> )

Coefficient ( AC )  
cc. 21-30

Enter the intercept for the  
non-ohmic cell polarization  
equation during charge.  
( volts )

Coefficient ( BC )  
cc. 31-40

Enter the slope coefficient  
for the non-ohmic cell  
polarization equation during  
charge.  
( v.cm<sup>2</sup>/amp )

Converter Charging Voltage (CAPVC )  
cc. 41-50

Enter the converter charging  
voltage.  
( volts )

CHARGE FLOW CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CHRG FLOW																																																																															

## Charge Flow Card

Reactant 1 ( F1C )  
cc. 11-20

Enter the solution flow rate  
per cell for reactant 1 during  
charge as:

$$f1c = \frac{\text{moles of reactant per unit time}}{\text{rate of generation of the charged state of reactant}}$$

( - )

Reactant 2 ( F2C )  
cc. 21-30

Enter the solution flow rate  
per cell for reactant 2 during  
charge as:

$$f2c = \frac{\text{moles of reactant per unit time}}{\text{rate of generation of the charged state of reactant}}$$

( - )

DENSITY CARD

										REACTANT 1 (gm/cm <sup>3</sup> )										REACTANT 2 (gm/cm <sup>3</sup> )																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
DENSITY																																																																															

Density Card

Reactant 1 Density ( RHO1 )  
cc. 11-20

Enter the average solution  
density( reactant and  
supporting electrolyte) for  
reactant 1 solution.  
( gm/cm3 )

Reactant 2 Density ( RHO2 )  
cc. 21-30

Enter the average solution  
density( reactant and  
supporting electrolyte) for  
reactant 2 solution.  
( gm/cm3 )

# DISCHARGE CARD

																				NON-OHMIC CELL POLARIZATION																																																											
																				intercept																														slope																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
DISCHARGE																																																																															



Discharge Card

cc. 11-20

\*\*\*EMPTY FIELD\*\*\*

Coefficient ( AD )  
cc. 21-30

Enter the intercept for the  
non-ohmic cell polarization  
equation during discharge.  
( volts )

Coefficient ( BD )  
cc. 31-40

Enter the slope coefficient  
for the non-ohmic cell  
polarization equation during  
discharge.  
( v.cm<sup>2</sup>/amp )

DISCHARGE FLOW CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
D.H. RG FLOW																																																																															

## Discharge Flow Card

Reactant 1 ( F1D )  
cc. 11-20

Enter the solution flow rate  
per cell for reactant 1 during  
discharge as:

moles of reactant per  
unit time  
f1d = -----  
rate of generation of the  
discharged state of  
reactant

( - )

Reactant 2 ( F2D )  
cc. 21-30

Enter the solution flow rate  
per cell for reactant 2 during  
discharge as:

moles of reactant per  
unit time  
f2d = -----  
rate of generation of the  
discharged  
state of reactant

( - )

### EFFICIENCY CARD

										RECTIFICATION										INVERSION										THERMAL										Faradaic																																							
										charge										discharge																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
EFFICIENCY																																																																															

Efficiency Card

Rectifying Efficiency ( ER )  
cc. 11-20

Enter the AC to DC rectifying  
efficiency factor.  
( 0 < ER < 1 )

Inversion Efficiency ( EI )  
cc. 21-30

Enter the DC to AC inversion  
efficiency factor.  
( 0 < EI < 1 )

Thermal Efficiency ( ET )  
cc. 31-40

Enter the cell thermal  
efficiency factor as the ratio  
of the free energy of reaction  
to the enthalpy of reaction.  
( 0 < ET < 1 )

Faradaic Cell Efficiency ( EFC )  
cc. 41-50

Enter the Faradaic cell  
efficiency factor during  
charge.  
( 0 < EFC < 1 )

Faradaic Cell Efficiency ( EFD )  
cc. 51-60

Enter the Faradaic cell  
efficiency factor during  
discharge.  
( 0 < EFD < 1 )

ELECTROLYTE CONCENTRATION CARD

										SOLUTION 1 (moles/l.)										SOLUTION 2 (moles/l.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ELEC CONC																																																																															

Electrolyte Concentration Card

Solution 1 ( C1S )  
cc. 11-20

Enter the initial  
concentration of supporting  
electrolyte in solution 1.  
( moles/litre )

Solution 2 ( C2S )  
cc. 21-30

Enter the initial  
concentration of supporting  
electrolyte in solution 2.  
( moles/litre )

ELECTRONS TRANSFERRED CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ELECTRONS																																																																															



Electrons Transferred Card

Reactant 1 ( Z1 )  
cc. 11-20

Enter            the            electrons  
transferred       per       mole    of  
reactant 1.  
( eq/mole )

Reactant 2 ( Z1 )  
cc. 21-30

Enter            the            electrons  
transferred       per       mole    of  
reactant 2.  
( eq/mole )

# HEAT CAPACITY CARD

										REACTANT 1 (cal/gm.deg C.)										REACTANT 2 (cal/gm.deg C.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
H.T. CAPACITY																																																																															

### Heat Capacity Card

Reactant 1 Heat Capacity ( CP1 )  
cc. 11-20

Enter the average solution  
heat capacity( reactant and  
supporting electrolyte) for  
reactant 1 solution.  
( cal/gm.deg C )

Reactant 2 Heat Capacity ( CP2 )  
cc. 21-30

Enter the average solution  
heat capacity( reactant and  
supporting electrolyte) for  
reactant 2 solution.  
( cal/gm.deg C )

## MEMBRANE CARD

[illegible]

Membrane Card

Thickness ( DELTA )  
cc. 11-20

Enter the membrane thickness.  
( cm )

Resistivity ( RHO )  
cc. 21-30

Enter the membrane specific  
resistivity.  
( ohm.cm )

# MOLECULAR WEIGHT CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
M.O.L.E.W.E.I.G.H.T																																																																															

Molecular Weight Card

Reactant 1 ( MW1 )  
cc. 11-20

Enter the molecular weight of  
reactant 1.  
( - )

Reactant 2 ( MW2 )  
cc. 21-30

Enter the molecular weight of  
reactant 2.  
( - )

POWER CARD

[illegible]



Power Card

Charge Power ( SCRPC )  
cc. 11-20

Enter the time averaged  
charging power.  
( mw )

Charge Time ( TC )  
cc. 21-30

Enter the charging time.  
( hours )

Discharge Power ( SCRPD )  
cc. 31-40

Enter the time averaged  
discharge power.  
( mw )

Discharge Time ( TD )  
cc. 41-50

Enter the discharging time.  
( hours )

Note:

Three of these four variables must be entered and the program will calculate the fourth. If all four are specified, the program will default to calculate the discharge power if it is a base case. For a parametric case the program will solve for the quantity it solved for in the previous case; however, the user can override this by putting a '-1' in the field corresponding to the desired unknown variable.

POWER CONDITIONING CARD

[illegible]

Power Conditioning Card

Power Conditioning Cost, ( CPCI )  
cc. 11-20

Enter the power conditioning  
installation cost.  
( \$/kw )

REACTANT CONCENTRATION CARD

										REACTANT 1 (moles/l.)										REACTANT 2 (moles/l.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
REACCONS																																																																															

Reactant Concentration Card

Reactant 1 ( C1 )  
cc. 11-20

Enter the initial  
concentration of reactant 1.  
( moles/litre )

Reactant 2 ( C2 )  
cc. 21-30

Enter the initial  
concentration of reactant 2.  
( moles/litre )

SOLUTION COST CARD

[illegible]

Solution Cost Card

Reactant 1 ( CR1 )  
cc. 11-20

Enter the cost of reactant 1  
in solution form.  
( \$/kg )

Reactant 2 ( CR2 )  
cc. 21-30

Enter the cost of reactant 2  
in solution form.  
( \$/kg )

Supporting electrolyte ( CSE )  
cc. 31-40

Enter the cost of the  
supporting electrolyte.  
( \$/kg )

Molecular weight ( MWSE )  
cc. 41-50

Enter the molecular weight of  
the supporting electrolyte.  
( - )

STACK SIZE CARD

[illegible]



Stack Size Card

Width { DELTSW )  
cc. 11-20

Enter the stack installation  
clearance, width.  
( cm )

Height { DELTSH )  
cc. 21-30

Enter the stack installation  
clearance, height.  
( cm )

Length { DELTSL )  
cc. 31-40

Enter the stack installation  
clearance, length.  
( cm )

TEMPERATURE CARD

										CELL TEMPERATURE (°C)										AMBIENT TEMPERATURE (°C)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
TEMP																																																																															

Temperatures Card

Cell Temperature ( TCELL )  
cc. 11-20

Enter the average cell  
temperature.  
( deg. C )

Ambient Temperature (TAIR )  
cc. 21-30

Enter the average ambient  
temperature.  
( deg. C )

### TRAILER COST CARD

[illegible]

Trailer Cost Card

Piping Cost ( CTP )  
cc. 11-20

Enter the trailer internal  
piping cost.  
( \$/kw )

Busbar Cost ( CTBB )  
cc. 21-30

Enter the trailer internal  
busbar and electrical  
connector cost.  
( \$/kw )

Structurals Cost ( CTS )  
cc. 31-40

Enter the trailer internal  
structurals cost.  
( \$/kw )

Instrumentaion Cost ( CTI )  
cc. 41-50

Enter the trailer internal  
instrumentaion cost.  
( \$/kw )

Installation Cost ( CI )  
cc. 51-60

Enter the trailer installation  
cost.  
( \$/kw )

TRAILER SIZE CARD

[illegible]

Trailer Size Card

Height ( THUS )  
cc. 11-20

Enter the external height of a  
shippable trailer.  
( feet )

Width ( TWUS )  
cc. 21-30

Enter the external width of a  
shippable trailer.  
( feet )

Length ( TLUS )  
cc. 31-40

Enter the external length of a  
shippable trailer.  
( feet )

Trailer Clearance ( DELTT )  
cc. 41-50

Enter the inboard clearance in  
a shippable trailer.  
( cm )

ULLAGE CARD

	REACTANT 1										REACTANT 2										TANKS																																																										
																					REACTANT 1					REACTANT 2																																																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ULLAGE																																																																															



Ullage Card

Reactant 1 ( FT1 )  
cc. 11-20

Enter the solution 1 inventory  
factor.  
( - )

Reactant 2 (FT2)  
cc. 21-30

Enter the solution 2 inventory  
factor.  
( - )

Reactant 1 Tank ( FTU1 )  
cc. 31-40

Enter the ullage factor for  
the tank holding reactant 1.  
( - )

Reactant 2 Tank ( FTU2 )  
cc. 41-50

Enter the ullage factor for  
the tank holding reactant 2.  
( - )

# TITLE CARDS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
XTITLE																																																																															
XTITLE																																																																															

## Case Delimiter And Title Cards

Title Cards  
cc. 1-10

Enter '\*TITLE' in columns 1-6 to indicate that the next cards are not data cards but title cards that the user can submit for each case for identification purposes. The user may submit up to five cards containing descriptive information and they must be followed with another '\*TITLE' card. This block of cards may be submitted at any time in the case input data and the user can submit title cards for each parametric case if he so desires.

The title cards are not erased when new ones are read in but instead they are overwritten. This way the user may change only the first card(s) in a set of title cards and retain the other(s) as is. Therefore it is suggested that descriptive material that pertains to several cases be on the last title card(s). In this way the first card(s) can be overwritten in each parametric case with less effort and still provide the full complement of the information.

## Case Delimiter And Title Cards

Keyword Field  
cc. 1-10

Enter '\*END' in columns 1-4 to indicate that the following data is a new base case. However, this card is not needed for the first base case.

Enter '\*PARA' in columns 1-5 to indicate that the following data is to modify the present case. There is no limit to the number of \*PARA cards that may be submitted in a single run.

## Program Structure

### Overall Structure

The Storage Battery Program is divided into four phases:

- o Input
- o Electrochemical calculations
- o Economic calculations
- o Output

The flow of control proceeds in order through the four phases of the program and repeats the cycle until an end of file is sensed on input.

If the program detects an error in any phase it will return immediately to the input phase to process more data.

### Input Phase

The subroutines comprising the input phase are:

INPUT ---- supervisor  
BLOCK DATA  
CHECK  
GETCRD  
PRINT

### Electrochemical Calculation Phase

There is only one subroutine in the electrochemical calculation phase and that is CALC.

Economic calculation phase

The subroutines comprising the  
economic calculation phase are:

ECON ----- supervisor  
FNCETF  
FNCVPC  
ZCOOL  
ZFILTER  
ZPUMP  
ZTANK

Output Phase

The subroutines comprising the  
output phase are:

OUTPUT ----- supervisor  
OUT1  
OUT2  
OUT3

Subroutine Descriptions

## MAIN

This routine controls the flow through the various phases of the program. If an error is detected in any phase of the program, this routine will direct the program back to the input phase to process more data.

## BLOCK DATA

This routine initializes all the arrays and scalars at the beginning of the program. It also contains the names of the allowable keywords for the input cards and control information for storing the input data.

The array 'CARD' stores the allowable keywords and there are two other arrays associated with it, 'NUM', AND 'ISLOT'. The value of 'NUM(I)' is the number of data fields on the card with the keyword of 'CARD(I)'. The value of 'ISLOT(I)' points to the position in array 'A' right above the place where the information on 'CARD(I)' is to be stored. (see INPUT ).

## CALC

The routine follows steps 1 thru 33 in the 'Request For Proposal' which describes the simplified equations for Model 1. The routine determines which power variable is unknown (either by a zero entry, a '-1' entry, or the previous unknown variable ) and if it is not the discharge power, it will solve for it directly. Then, the routine proceeds step by step as defined by the RFP to calculate the discharge power and all intermediate variables. The calculated variables are stored in arrays 'C', 'D', and 'E' in the same order in which they are printed by subroutine OUT1.

At several places the routine checks for zero quantities which are used as divisors. If any are detected, the routine branches to an error message and returns to MAIN.

## CHECK

This routine checks all input data and flags those data items that are zero and are used as divisors in the calculations. If any are found, the program prints out those variables, sets an error code and returns control to MAIN.

This routine is called each time the program completes the input phase. In this way, a data item that was previously zero may be modified such that the program will proceed to the calculation phase.



## ECON

This routine handles the bulk of all the economic calculations. It sets up all the necessary data to call the costing routines for the various pieces of equipment in the system. However, it performs the trailer and power conditioning calculations itself.

This routine sets up all the output data except the electrochemical data which is done in subroutine CALC. All data which is to be printed out is stored in an array in the order in which it is to be printed. The costing and sizing calculations are discussed in the appropriate subroutine for each functional section.

The first calculations determine the flow rates in the system, heat duties, and power requirements. Next, the routine does all the cell, stack, and trailer sizing and cost calculations. Next, it sets up the appropriate data for the various functional section equipment, calls the proper routine, and stores the results. The results are stored in scalar variables but they are equivalenced to an output array for convenient I/O.

## FNCETF

This is a table lookup routine to determine the cooler  $F_t$  factor based on the temperature effectiveness factor.

## FNCVPC

This is a table lookup routine to determine the power conditioning cost rate in \$/kw as a function of the voltage.

## GETCRD

This routine handles all input processing and determines the keyword on each card. If it is a data card, control is returned immediately to subroutine INPUT. If it is a control card(\*TITLE, \*END, \*PARA), this subroutine will set the appropriate keys and store any necessary information before it returns to INPUT.

## INPUT

This routine controls the input to the program and stores all the input data. All input data is stored in array 'A' in the proper slot corresponding to its keyword(see NUM and ISLOT in BLOCK DATA ).

When the input processing is completed(\*END or \*PARA) this subroutine loads the non-zero entries of array 'A' into a similar array 'B'. Array 'B' is then passed on to the rest of the program.

This routine calls subroutines CHECK, and PRINT. If no errors were detected either by CHECK, GETCRD, or INPUT the routine returns to MAIN. Otherwise, the program stays in the input phase and begins to process additional data.

## OUTPUT

This routine is the output phase supervisor and controls the output of the various tables of data. Although the routine is rather trivial, it provides a handy framework for installing additional user control over the output at a later date. A prime example of this would be some sort of an abort print should an error occur. Then this routine would call only those output reports unaffected by the error.

## OUT1

This routine prints the results of the electrochemical calculations. The FORTRAN variables are printed out also for the convenience of the user. All of the information is calculated in subroutine CALC and stored in arrays 'C', 'D', and 'E'.

## OUT2

This routine prints out the summary of the economic calculations. These data are calculated in subroutine ECON and the appropriate functional section equipment subroutines.

## OUT3

This routine prints out the details of the economic calculations. These data are calculated in subroutine ECON and the appropriate functional section equipment subroutines.

## PRINT

This routine prints the input data as stored by the program. The FORTRAN variables are printed out for the user's convenience along with the proper units.

This printout normally will only appear for base case data. In many cases, the data will be nearly identical for a parameter case and this printout is suppressed. The echo print provided by GETCRD will report the changes made by the user to the base case. However; should the user want to see the input phase print out for a parameter case, he need only supply a '1.0' in the first data field on the \*PARAM card that precedes the parameter case data.

## ZCOOL

This routine handles the sizing and costing of the air fin coolers in the plant. The coolers are designed to remove the waste heat produced in the trailers both during charge and discharge. Therefore, they are sized to meet the maximum heat duty requirement which can be during either the charge or discharge cycle.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZCOOL, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	duty	mbtu
3	plot area	ft <sup>2</sup>
4	fan power	hp
5	-	
6	cooler cost	k\$
7	number of coolers	-

The curve fits used in the cooler calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln(cooler cost)	ln(area)
ln(fan hp)	ln(area)

## ZFILTER

This routine handles the sizing and costing of the filters in the plant.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZFILTER, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	number of filters	-
3	size	gpm=275.
4	filter cost	k\$

The curve fit used in the filter calculations is:

<u>y-axis</u>	<u>x-axis</u>
ln(filter cost)	ln(gpm)
sizing- - - none	- - - - -
- - (one size fits all)	- -

## ZPUMP

This routine handles the sizing and costing of the pumps in the plant. The program picks three pumps each one having the capacity of one-half the flow rate. In other words, two pumps are used at full capacity plus a third one to be used as a spare. Should the largest pump size available be inadequate to handle one-half the flow rate, the design basis is changed from three 50% pumps to four  $33\frac{1}{3}\%$  pumps (three operate at full capacity plus a fourth one as a spare). The design basis may change several times in order to accomodate the flow rate.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZPUMP, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	number of pumps	-
3	size	gpm
4	pump cost	k\$
5	motor power	hp

The curve fits used in the pump calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln (pump cost)	sqrt (gpm)
ln (hp)	ln (gpm)

## ZTANK

This routine handles the sizing and costing of the storage tanks in the plant. The program sizes one tank for each reactant plus one common spare. Should the maximum available tank size be inadequate the program will change the design basis to be two equal sized tanks for that reactant. The design basis may change independently for each reactant several times until the tank sizing calculations are complete. Regardless of how many tanks are required to hold a single reactant, there will only be one spare tank of the same capacity as the largest tank.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZTANK, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	volume of fluid	bbl
2	number of tanks	-
3	tank cost	k\$
4	mixer power	hp

The curve fits used in the tank calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln(tank cost)	ln(bbl)
mixer power	= 0.35*kbb1



## APPENDIX 1

### Outline of Computational Procedures Used in Stage 1 Model of Redox Energy Storage Systems

The following is a brief outline of the computational procedures used in the Stage 1 Model of Redox Energy Storage Systems. This outline presents the equations used, together with necessary descriptive material, to assist the user of the Stage 1 Model computer program in interpreting the program output. Additional details of the program parameters, including suggested baseline values are given in Attachment 1. Supplementary discussion of specific program features, including equipment sizing, sparing and costing procedures are included elsewhere in the program documentation package.

#### Redox System Overview

The Redox Energy Storage System contains a number of process and equipment sections including:

- Redox Converter Section.
- Power Conditioning Section
- Tankage Section
- Pump Section
- Filter Section
- Cooler (Heat Exchanger) Section

These sections are organized into a complete system, as shown in the baseline plot plan given in Figure 1. The equipment sizing and costing procedures for each section are described in the following paragraphs.

#### System Performance Evaluation

NASA has provided an outline of the Stage 1 Model Redox System performance evaluation procedure. This is given in Attachment 2, and will not be discussed in detail. As specific calculated parameters are called for below, reference will be made to the relevant step number in Attachment 2.

#### Cost Estimation Approach

Simplified cost estimating procedures are used in the Stage 1 Model, consistent with the level of detail and sophistication used to calculate the system performance characteristics. Costs are estimated for the process section, using the bases described below for each section. Generally, these estimates are made by interpolation from cost curves that were derived from cost estimates made for individual test cases that covered a broad range of equipment size. Associated piping and manifolding requirements are factored into the overall section equipment cost. The process section equipment costs (tankage, pumps, filters and coolers) have been reported as total installed costs, on a 1Q76 basis (instantaneous costs). Materials and equipment are assumed purchased on the Gulf Coast, with installation in the S.E. USA.

In general, indirect costs include detailed engineering at 5%, erection fees at 2% and basic engineering at 2% of direct materials costs. The tanks and tank linings are assumed to be subcontracted items, involving the basic engineering charge only. Preliminary analysis showed that the process section installation was not labor intensive. That is, labor costs were a small fraction of total direct costs. A 20% project contingency is applied, to account for unexpected site-specific factors. The costs of land and site improvement are not included, since we assume that the Redox system is installed at existing utility facilities.

The costing approach for the Redox converter and power conditioning sections is somewhat different. Direct equipment costs are calculated in a straight-forward manner. Then, suitable cost factors, generally expressed on a \$/kw of power basis, are used to estimate the total installed cost. This factor approach has proved useful in other studies of large utility - scale electrochemical systems.

Finally, the solution inventory costs are calculated, including both reactants and supporting electrolyte.

#### Redox Converter Section

This section consists of installed, shippable trailers containing assembled Redox converter stacks. The stacks, in turn, contain a number of individual bipolar plate cells. A schematic of the cell design is shown in Figure 2. This figure also indicates the individual cell component dimensions.

##### • Unit Cell Size

- + Calculate unit cell thickness (see Attachment 1 for notation and dimensions):

$$t_{\text{cell}}, \text{ cm} = \gamma_c + 2e + \delta + 2 \tau$$

- + Calculate net volume of plastic per cell (neglecting corrections for manifold holes and noting that cell size,  $a$ , is available from Step 12 in Attachment 2):

$$v_{\text{CP}}, \text{ cm}^3 = \left[ 1.96 t_{\text{cell}} - 1.1 \gamma_c - 2\tau - (2e+\delta)1.1 \right] a^2$$

- + Calculate volume of conductive current collector (bipolar plate) per cell:

$$v_{\text{CC}}, \text{ cm}^3 = (0.333 \tau + 1.1 \gamma_c) a^2$$

- + Calculate membrane area per cell:

$$A_{\text{cm}}, \text{ cm}^2 = 1.10 a^2$$

- + Calculate total electrode deposit weight per cell (total for 2 electrodes).

$$w_{\text{CE}}, \text{ gms} = 2.2e\rho_E a^2$$

• Stack End Plates

Calculate individual end plate thickness:

$$t_E, \text{ cm} = \gamma_E + 1$$

+ Calculate total volume of end plate plastic (for 2 endplates):

$$V_{EPP}, \text{ cm}^3 = (1.96 + 0.86 \gamma_E - \frac{1.2}{a}) a^2$$

+ Calculate total volume of end plate conductive material (for 2 end plates):

$$V_{EPC}, \text{ cm}^3 = 2 (1.1 \gamma_E a^2 + 6a)$$

• Stack Size

+ Assume all cells in stack are connected in series electrically, giving desired value of charging voltage,  $V_c$ . Then, base stack length is:

$$l_s, \text{ cm} = n_s t_{\text{cell}} + 2 t_E$$

where:  $n_s$  = Number of cells in series (Step 10 in Attachment 2)

+ Calculate bare stack height and width, equal to individual cell height and width.

$$h_s, \text{ cm} = w_s, \text{ cm} = 1.4a$$

+ Assume installation clearances, providing room for stack manifolding, busbars and support (see Figure 3), all in cm.

$$\text{Clearance width} = \delta_{SW}$$

$$\text{Clearance height} = \delta_{SH}$$

$$\text{Clearance length} = \delta_{SL}$$

+ Calculate installed stack volume

$$V_{\text{STACK, INST}}, \text{ m}^3 = \frac{(1.4a + 2\delta_{SH})(1.4a + 2\delta_{SW})(l_s + 2\delta_{SL})}{10^6}$$

• Shippable Trailer Assembly

+ Assume stacks are assembled in shippable trailers. Largest trailer dimensions are:

$$\text{Height} = T'_H, \text{ ft} = 10$$

$$\text{Width} = T'_W, \text{ ft} = 10$$

$$\text{Length} = T'_L, \text{ ft} = 40$$

Convert these dimensions to cm, yielding, respectively,  $T_H$ ,  $T_W$  and  $T_L$ .

- + Assume total in-board clearance in any direction within trailer is  $\Delta_T$ , cm.

- + Calculate available internal trailer volume for stack packing:

$$V_T, \text{ m}^3 = \frac{(T_H - \Delta_T)(T_W - \Delta_T)(T_L - \Delta_T)}{10^6}$$

- + Calculate number of stacks per trailer, permitting fractional stack values and assuming no restraints on packaging geometry:

$$N_{ST} = \frac{V_T}{V_{STACK, INST}}$$

- + Calculate number of cells per trailer

$$N_{CT} = n_s N_{ST}$$

- + Calculate total number of trailers in Redox converter sections, recalling that total number of cells,  $N$ , is available (see Step 12 in Attachment 2):

$$N_T = \frac{N}{N_{CT}}$$

#### • Stack Cost

- + Calculate unit cell material cost, using assumed parameters defined in Attachment 1:

$$C_{CELL}, \$ = \frac{V_{CP} \rho_{CP} C_{CP}}{10^3} + \frac{V_{CC} \rho_{CC} C_{CC}}{10^3} + \frac{W_{CE} C_E}{10^3} + \frac{A_{cm} C_m}{10^4}$$

- + Calculate total end plate cost, assuming end plate plastic and conductive material are same as those used in cell construction:

$$C_{EP}, \$ = \frac{V_{EPP} \rho_{CP} C_{CP}}{10^3} + \frac{V_{EPC} \rho_{CC} C_{CC}}{10^3}$$

- + Calculate stack material cost:

$$C_{STACK MATL}, \$ = n_s C_{CELL} + C_{EP}$$

- + Calculate fabricated and assembled stack cost, assuming a value for

$$f_m = \frac{\text{Stack Manufactured Cost}}{\text{Stack Mat'l's Cost}};$$

$$C_{STACK, MANUF}, \$ = f_m C_{STACK MAT'L}.$$

• Trailer and Redox Converter Section Cost

- + A trailer consists of  $N_{ST}$  stacks and associated internal piping, busbars, structural supports and instrumentation. The cost of the last four items will be calculated on the basis of the maximum trailer power level, which may occur in charge or discharge operation. It is necessary to determine each power level.

- + In charging mode, calculate stack power:

$$P_{SC}, \text{ kw} = \frac{P_C a^2 M_S}{10^3}$$

and trailer power:

$$P_{TC}, \text{ MW} = \frac{N_{ST} P_{SC}}{10^3}$$

Repeat for discharge operations:

$$P_{SD}, \text{ kw} = \frac{P_D a^2 n_S}{10^3}$$

$$P_{TD}, \text{ MW} = \frac{N_{ST} P_{SD}}{10^3}$$

- + Pick larger value of  $P_{TC}$  and  $P_{TD}$  and call this maximum trailer power,  $P_{T \text{ MAX}}$ , MW.
- + Calculate trailer manufactured cost, assuming factors for trailer internals costs (see Attachment 1):

$$C_{\text{TRAILER, MANUF}}, \$ = N_{ST} C_{\text{STACK MANUF}} + P_{T \text{ MAX}} \left[ C_{TP} + C_{TBB} + C_{TS} + C_{TI} \right] 10^3$$

- + Calculate installed trailer cost, assuming a power-related factor for installation (foundation and hook-up) costs:

$$C_{\text{TRAILER, INSTALLED}}, \$ = C_{\text{TRAILER, MANUF}} + C_I P_{\text{MAX}} 10^3$$

- + Calculate installed cost of total Redox converter section:

$$C_{\text{TOTAL TRAILER INSTALLED COST}}, \$ = N_T C_{\text{TRAILER, INSTALLED}}$$

Power Conditioning Section

The power conditioning section consists of an inverter/rectifier and transformer equipment for tie-in to a 13.5 kv electric utility grid. This section will be costed on the basis of the maximum input power level, during charge or discharge, together with the associated voltage level. Prepare the following matrix.

<u>Operating Mode</u>	<u>Maximum Section Input Power Level, MW</u>	<u>DC Voltage Level, Volts</u>
Charge	$P_C$	$V_C$
Discharge	$P_D$	$V_D (=n_s V_C)$

Select the maximum power situation and associated voltage and call these  $P_{PC}$  and  $V_{PC}$ , respectively.

• Power Conditioning Costs

- + Find power conditioning cost factor,  $C_{PC}$ , using  $V_{PC}$ . These factors were derived from Westinghouse report for current-fed, naturally-commutated equipment:

<u><math>V_{PC}</math>, Volts</u>	<u><math>C_{PC}</math>, \$/kw</u>
164	160
203	150
248	140
304	130
366	120
433	110
528	100
657	90
920	80
1560	70
2810	65

- + Calculate purchased cost of power conditioning equipment:

$$C_{\text{POWERCOND}}, \$ = C_{PC} P_{PC} 10^3$$

- + Calculate the total installed of power conditioning equipment, assuming a power level-related value,  $C_{PCI}$ , for installation costs:

$$C_{\text{POWERCOND INSTALLED}}, \$ = C_{\text{POWERCOND}} + C_{PCI} P_{PC} 10^3$$

Tankage Section

This section consists of "active" storage tanks for reactant solutions (reactants 1 and 2) and a "passive" spare tank equal in size to the largest individual active tank in the section. The tank sparing philosophy is given elsewhere in the documentation package.

- Tank Capacity

- + Values are available for the volume of solution (see Step 18 Attachment 2):

$$V_1 = \frac{M_1}{C_1} \quad \text{and} \quad V_2 = \frac{M_2}{C_2}$$

- + Calculate adjusted reactant and solution inventories, assuming factors,  $f_I$  for liquid hold-up in process equipment and Redox converter cells:

$$V_{1(\text{ADJUST})}, \text{ liters} = f_{I(1)} \frac{M_1}{C_2}$$

$$V_{2(\text{ADJUST})}, \text{ liters} = f_{I(2)} \frac{M_2}{C_2}$$

$$1(\text{ADJUST}), \text{ gm moles} = f_{I(1)} M_1$$

$$2(\text{ADJUST}), \text{ gm moles} = f_{I(2)} M_2$$

- + Calculate nominal tank volume, assuming tank ullage factors,  $f_{TU}$ , (see Attachment 1):

$$V_{T(1)}, \text{ liters} = f_{TU(1)} V_{1(\text{ADJUST})}$$

$$V_{T(2)}, \text{ liters} = f_{TU(2)} V_{2(\text{ADJUST})}$$

- + Select the largest tank volume and assume the common spare tank has the same volume.

• Tankage Cost

The tankage costs are calculated on the basis of the total installed costs shown in Figure 4. These costs include the subcontracted delivered and erected cost of the (painted) tank and tank pad, a subcontracted PVC tank liner, an associated spill wall section per tank, suitable mixers and associated PVC lined connecting piping (to the pumping section) and rubber-lined valves. In addition, the tank is assumed to be insulated, in the general case.

An estimate is also provided for the parasitic power associated with the mixers. This is shown in Figure 5.

Pump Section

This section contains suitable pumps for transferring reactant solution from the tankage section to the remaining system sections.

• Pump Size

The total solution flow rates are required, based on results obtained from previous subroutines (see Attachment 2).

- + Calculate the volumetric flow rates, during charge, for each reactant solution:

$$Q_{1C}, \text{ liters/sec} = \frac{f_{1C} S_{1C}}{C_1}$$

$$Q_{2C}, \text{ liters/sec} = \frac{f_{2C} S_{2C}}{C_2}$$

Calculate the corresponding solution weight flow rates,  $W_C$ , assuming an average solution density,  $\bar{\rho}$  (see Attachment 1):

$$W_{1C}, \frac{\text{kg}}{\text{sec}} = Q_{1C} \bar{\rho}_{\text{SOL } 1}$$

$$W_{2C}, \frac{\text{kg}}{\text{sec}} = Q_{2C} \bar{\rho}_{\text{SOL } 2}$$

- + Repeat above for discharge operation:

$$Q_{1D} = \frac{f_{1D} S_{1D}}{C_1} ; W_{1D} = Q_{1D} \bar{\rho}_{\text{SOL } 1}$$

$$Q_{2D} = \frac{f_{2D} S_{2D}}{C_2} ; W_{2D} = Q_{2D} \bar{\rho}_{\text{SOL } 2}$$



- + The number of pumps required for each reactant solution is calculated, based on the maximum volumetric solution flow rates (during charge or discharge), the assumed maximum capacity per pump (taken as 6200 gpm) and the sparing philosophy discussed elsewhere in the documentation package. It should be noted that the maximum pump capacity depends on the required pump discharge pressure, which cannot be calculated using the Stage I Model level of sophistication. We assume here that pump discharge pressure is about 200 psig.

- Pump Costing

The total installed cost per pump is estimated using the data curve in Figure 6. This curve represents the cost of the "optimal" pump type as a function of flow rate capacity. The value includes the cost of a pump with Hastelloy casing and internals, associated electrical driver motor, foundations, manifolding and an equivalent length of piping to connect to the filter section.

An estimate of the horsepower consumed by the driver motors is given in Figure 5. It should be noted that this is the maximum horsepower requirement, based on the maximum pump capacity and system operating condition. Thus, if charge and discharge operation involve substantially different flow rates, the parasitic power associated with the smaller flow rate will be over-estimated.

### Filter Section

The filter section contains a number of parallel-manifolded cartridge filter assemblies, each consisting of several filters in a single housing. Estimated maximum flow rate per assembly is 275 gpm, resulting in a considerable number of filters to accommodate the maximum solution flow rates. Filter number calculations are described elsewhere in this documentation.

- Filter Costs

The total installed cost of the filter section is estimated using the curve in Figure 7, based on total reactant flow rate. Again, PVC-lined housings and manifold piping are assumed.

### Cooler (Heat Exchanger) Section

This section consists of a number of modular, closed-loop, air-fin heat exchangers, designed to cool the effluent solutions from the Redox converter section. In order to size this section, it is necessary to carry out a system heat balance.

• System Heat Balance and Cooler Size

A system heat balance is calculated, using the approach shown in Figure 8. An adiabatic storage system is assumed, with heat generated in the Redox cells being dissipated in the heat exchangers. Earlier subroutines have calculated the waste heat generated during charge  $Q_C$  and discharge,  $Q_D$  (see Steps 22 and 28 in Attachment 2). Note that the units of  $Q$  are MW. It is assumed that the storage temperature (cell input temperature) is such that all solutions exit the Redox cells at the desired cell operating temperature,  $T_{CELL}$ .\*

- + Calculate the storage temperature required during charge operation, using the solution weight flow rates, assumed average heat capacities and  $Q_C$ :

$$T_{STORAGE\ C},\ ^\circ C = T_{CELL} - \frac{238.66\ Q_C}{[W_{1C}\ \bar{C}_{P1} + W_{2C}\ \bar{C}_{P2}]}$$

- + Repeat for discharge operation

$$T_{STORAGE\ D},\ ^\circ C = T_{CELL} - \frac{238.66\ Q_D}{[W_{1D}\ \bar{C}_{P1} + W_{2D}\ \bar{C}_{P2}]}$$

- + Note that  $T_{STORAGE} = T_{COOLER\ OUTLET}$ , so that value of  $T_{STORAGE}$  calculated above can be used to calculate size of air fin coolers.

- + Calculate heat duty for each reactant flow stream, during charge and discharge operation, assuming that individual stream duty is proportional to the weighted thermal flow rate:

$$Q_{COOL(1)C},\ BTU/hr = \left( \frac{W_{1C}\ \bar{C}_{P1}}{W_{1C}\ \bar{C}_{P1} + W_{2C}\ \bar{C}_{P2}} \right) Q_C\ (3.4095 \times 10^6)$$

$$Q_{COOL(2)C},\ BTU/hr = 3.4095 \times 10^6\ Q_C - Q_{COOL(1)C}$$

$$Q_{COOL(1)D},\ BTU/hr = \left( \frac{W_{1D}\ \bar{C}_{P1}}{W_{1D}\ \bar{C}_{P1} + W_{2D}\ \bar{C}_{P2}} \right) Q_D\ (3.4095 \times 10^6)$$

$$Q_{COOL(2)D},\ BTU/hr = 3.4095 \times 10^6\ Q_D - Q_{COOL(1)D}$$

---

\* The computer program calculations are arranged to display a negative value of  $Q$  when heat is generated and a positive value when heat is absorbed during operation. In the latter case, a heater section would be required to maintain desired cell temperature, but the program does not consider heating requirements.

- + Calculate plot plan area for individual stream cooler, using simplified procedure for air fins coolers, for charge and discharge operation:

- Calculate temperature effectiveness factor:

$$E_t = \frac{T_{\text{CELL}} - T_{\text{STORAGE}}}{T_{\text{CELL}} - T_{\text{AIR}}}$$

- Look up correction factor,  $F_T$ :

$E_t$	0	0.2	0.4	0.6	0.8	0.9
$F_t$	1.00	0.91	0.80	0.60	0.53	0.45

- Calculate exchanger plot area, for example:

$$PA(1)_C, \text{ ft}^2 = \frac{Q_{\text{COOL}}(1)C}{(400) F_T (T_{\text{CELL}} - T_{\text{AIR}})} \quad (1.8)$$

- Compare calculated plot areas for reactant 1 for charge and discharge. Select maximum area as design case. Calculate approximate cooling fan horsepower (see Figure 5):

$$\overline{P}(1), \text{ hp} = \frac{PA(1)}{10.76}$$

- Repeat for reactant 2.

#### \* Cooler Costs

The total installed cost of the coolers for each reactant stream is estimated using the curve in Figure 9, based on cooler plot area. The use of Hastelloy exchanger tubes was assumed.

#### Stored Solution Costs

Finally, the cost of stored solution inventory is estimated, using assumed delivered costs for each reactant (in solution form) and associated supporting electrolyte.

- + Calculate cost of stored reactants (see Attachment 1 for nomenclature):

$$C_{\text{SR}}(1), \$ = \frac{M_1(\text{ADJUST}) \text{ MW}_1 C_R(1)}{10^3}$$

$$C_{\text{SR}}(2), \$ = \frac{M_2(\text{ADJUST}) \text{ MW}_2 C_R(2)}{10^3}$$

+ Calculate cost of supporting electrolyte:

$$C_{SSE}, \$ = \left[ V_{1C}(\text{ADJUST}) \cdot C_{1S} + V_{2C}(\text{ADJUST}) \cdot C_{2S} \right] \frac{\text{MW}(\text{SE}) C_{SE}}{10^3}$$

+ Calculate delivered cost of stored solution inventory:

$$C_{SSI}, \$ = C_{SR(1)} + C_{SR(2)} + C_{SSE}$$

### Total Installed Investment Cost

The total equipment cost for the Redox storage system is calculated as the sum of tankage, pump, filter, cooler, Redox trailer and power conditioning installed costs. Total chemical cost, including both reactants and supporting electrolyte are added to obtain the total installed investment cost. Interim figures -of-merit are calculated, based on discharge operation:

$$\text{Power Investment Cost, } \frac{\$}{\text{Kw}} = \frac{\text{Total Installed Investment Cost}}{\text{Time Averaged AC Discharge Power}}$$

$$\text{Energy Investment Cost, } \frac{\$}{\text{KwH}} = \frac{\text{Power Investment Cost}}{\text{Discharge Time}}$$

### System Efficiency Analysis

Estimates of auxiliary power requirements and system energy storage efficiency are also made. The auxiliary power requirement includes pump driver, cooler fan and tank mixer usage. These are conservative (high) estimates, based on the maximum rating of the individual motors involved. The same estimate is used for charge and discharge operation. A "net" power is calculated. For charge, this is the sum of the "given" AC charging (input) power and the auxiliary power. For discharge, the difference between the AC discharge (output) power and the auxiliary power is used. Note that the charging auxiliary power is considered as a supplementary input, not deducted from the "given" charging power,  $P_C$ . An energy balance with fixed  $P_C$  input would require iterative procedures to obtain initial estimates of system size and auxiliary power, with subsequent adjustment of the DC power level,  $P_D$ . This procedure was considered too involved for the level of sophistication of the Stage 1 Model.

#### • Energy Storage Efficiency

+ Calculate energy storage efficiency, excluding auxiliary power consumption:

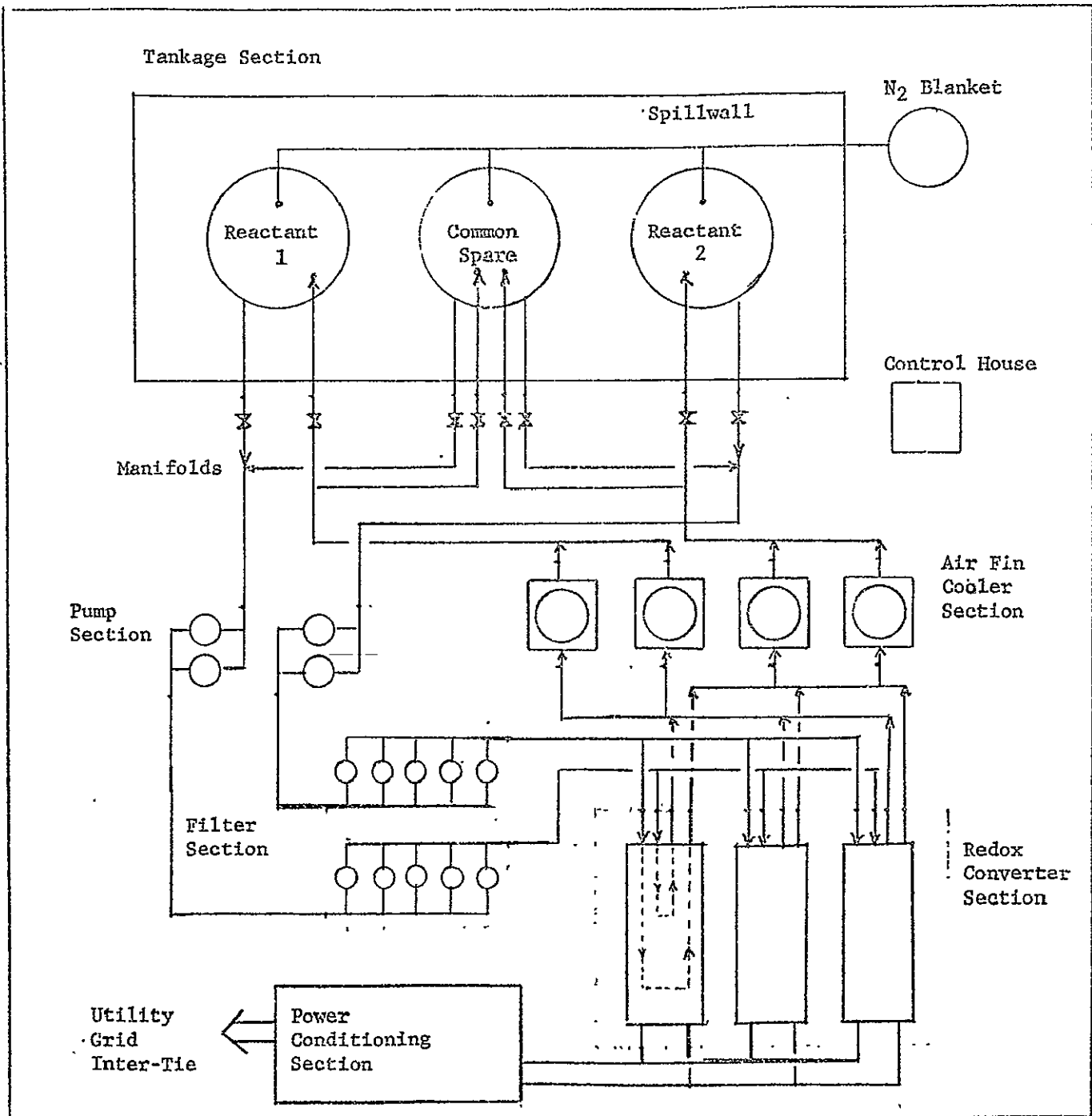
$$\text{Efficiency(Gross), \%} = \frac{P_D t_D}{P_C t_C} \times 100$$

- + Calculate energy storage efficiency, including auxiliary power consumption:

$$\text{Efficiency (Net), \%} = \frac{(P_D - P_{AUX}) \cdot t_D}{(P_C + P_{AUX}) \cdot t_C} \times 100$$

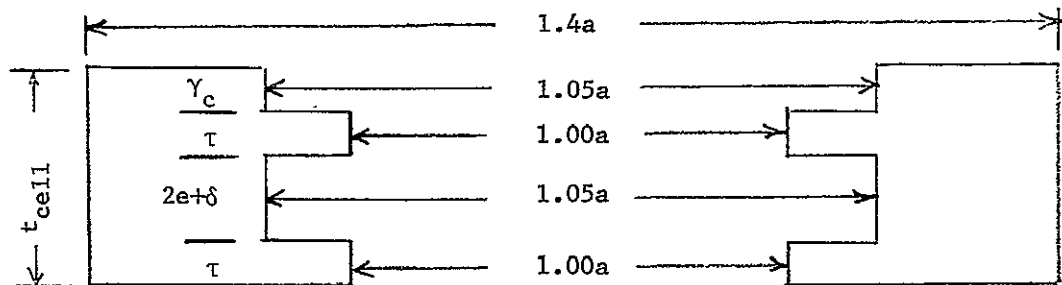
- + The program also calculates the maximum attainable energy storage efficiency and maximum discharge power, based on the Stage 1 Model logic and certain "assumed" parameters. The derivation of these quantities is described in Monthly Report No. 3.

Figure 1

Base-Line Plot Plan For Redox Storage System

Electrode Deposit  
Flow Channel  
Bipolar Plate  
Membrane  
Electrode Deposit  
Flow Channel  
Conductive Section  
Protruding Current Take-Off Tab  
(+)  
(-)  
Plate fin projection dimensions:  
Height  $\tau$   
Thickness 0.1cm (fixed)  
Length  $a$   
Spacing 0.5cm (fixed)  
End Plate  
Cell No. 1  
Cell No. 2  
End Plate  
Assembly (ways)  
 $t_{cell}$

Cell Frame  
Top View



Cell Frame  
Plan View

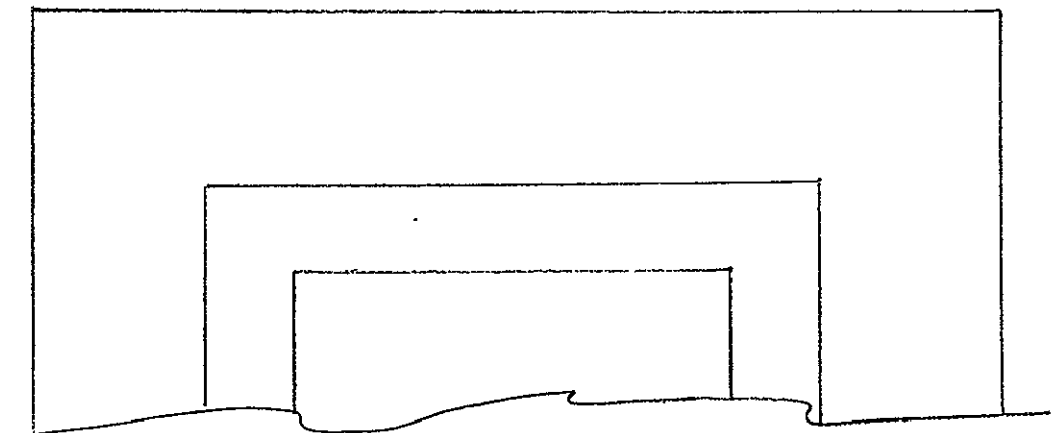


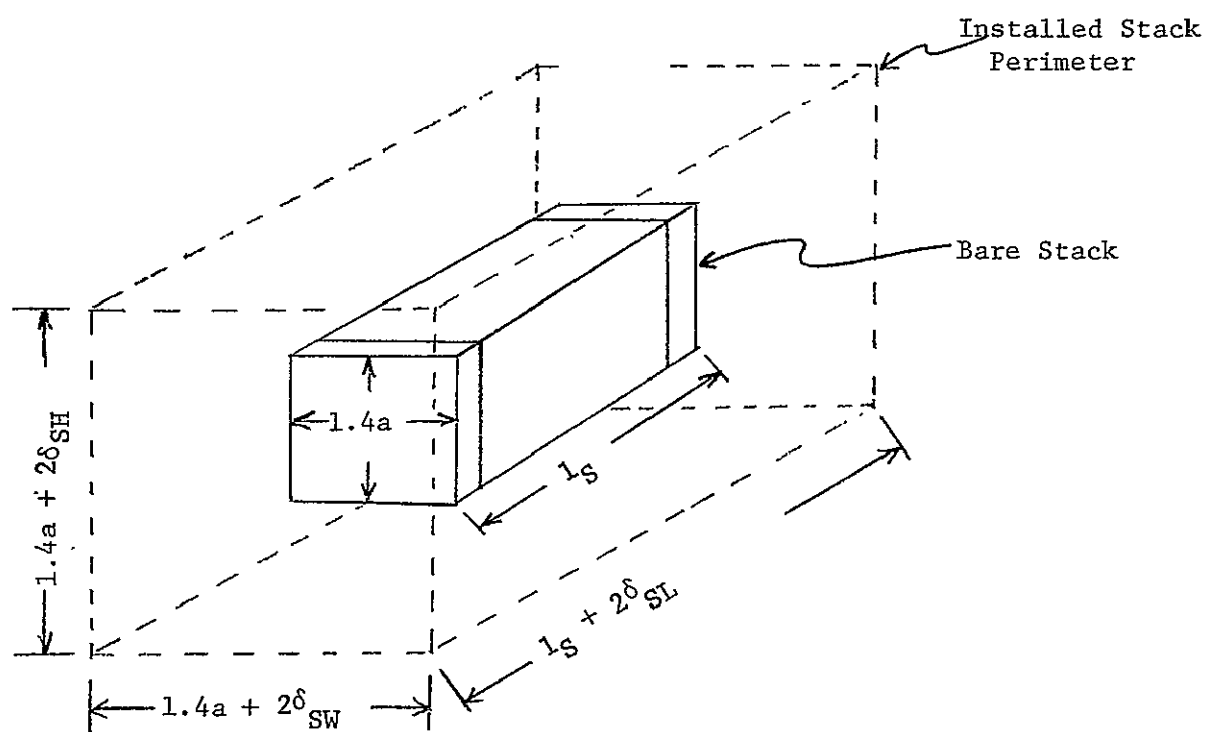
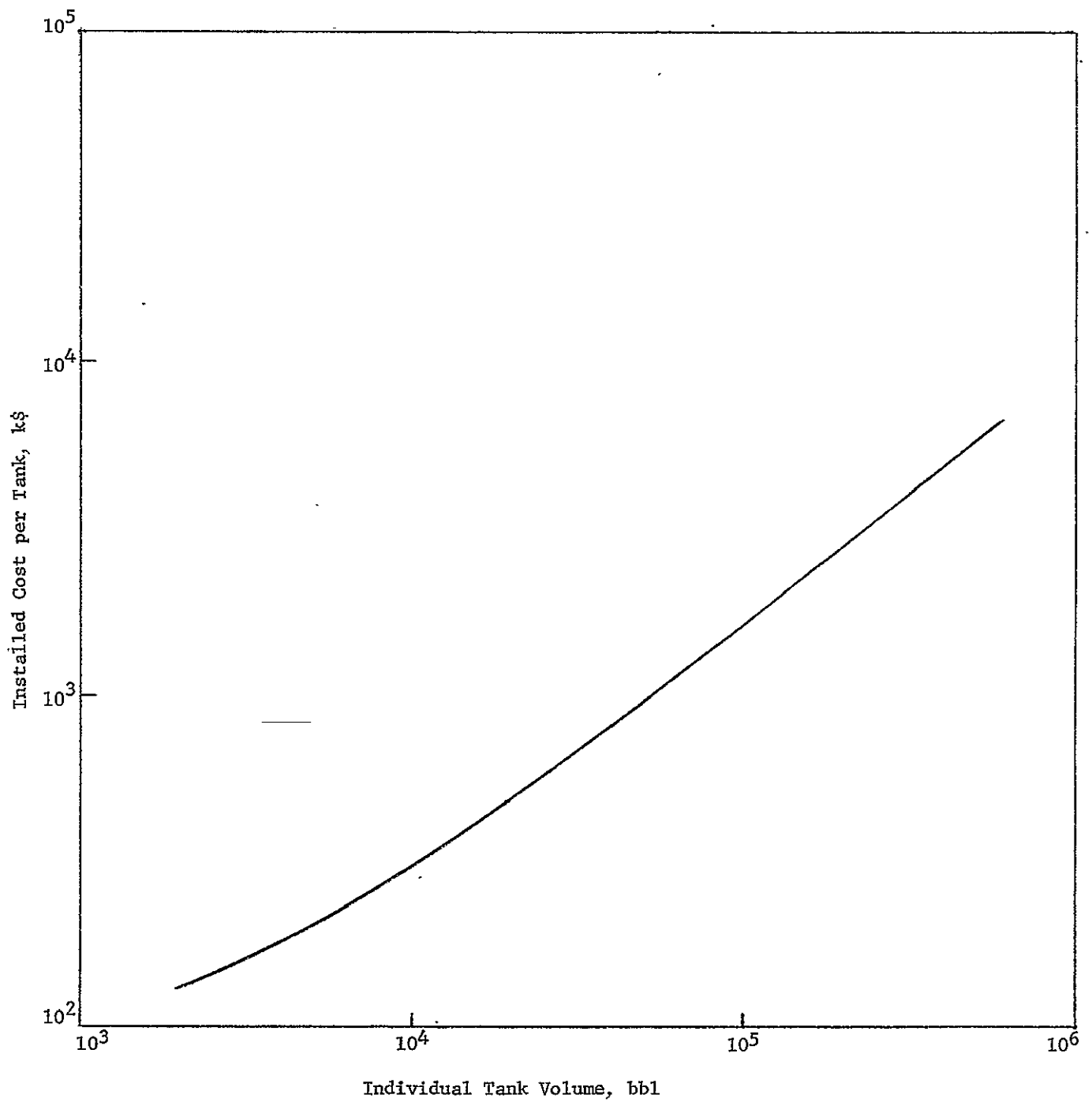
Figure 3Installed Stack Clearances



Figure 4Tankage Section Costs

Auxiliary Power Requirements

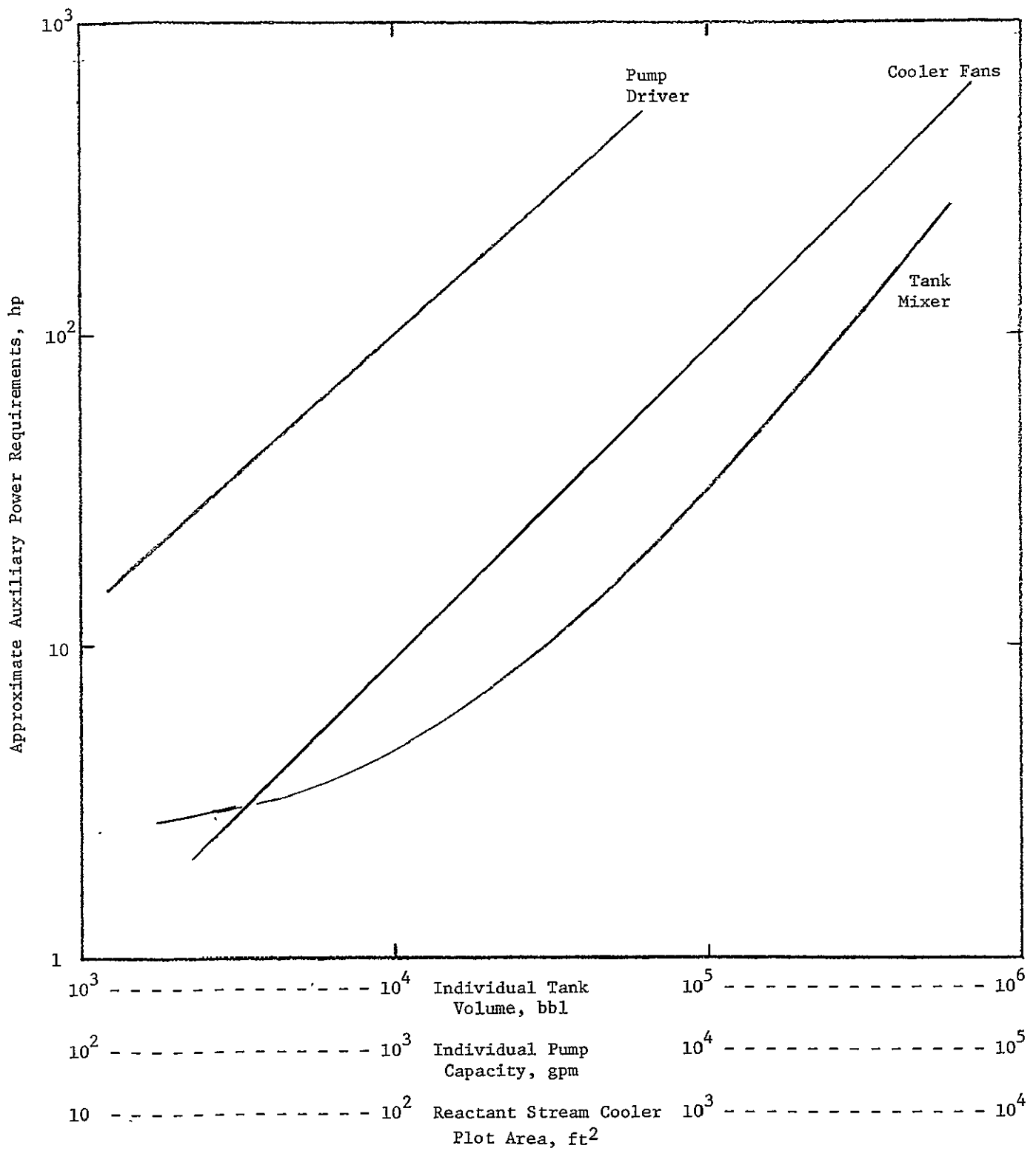


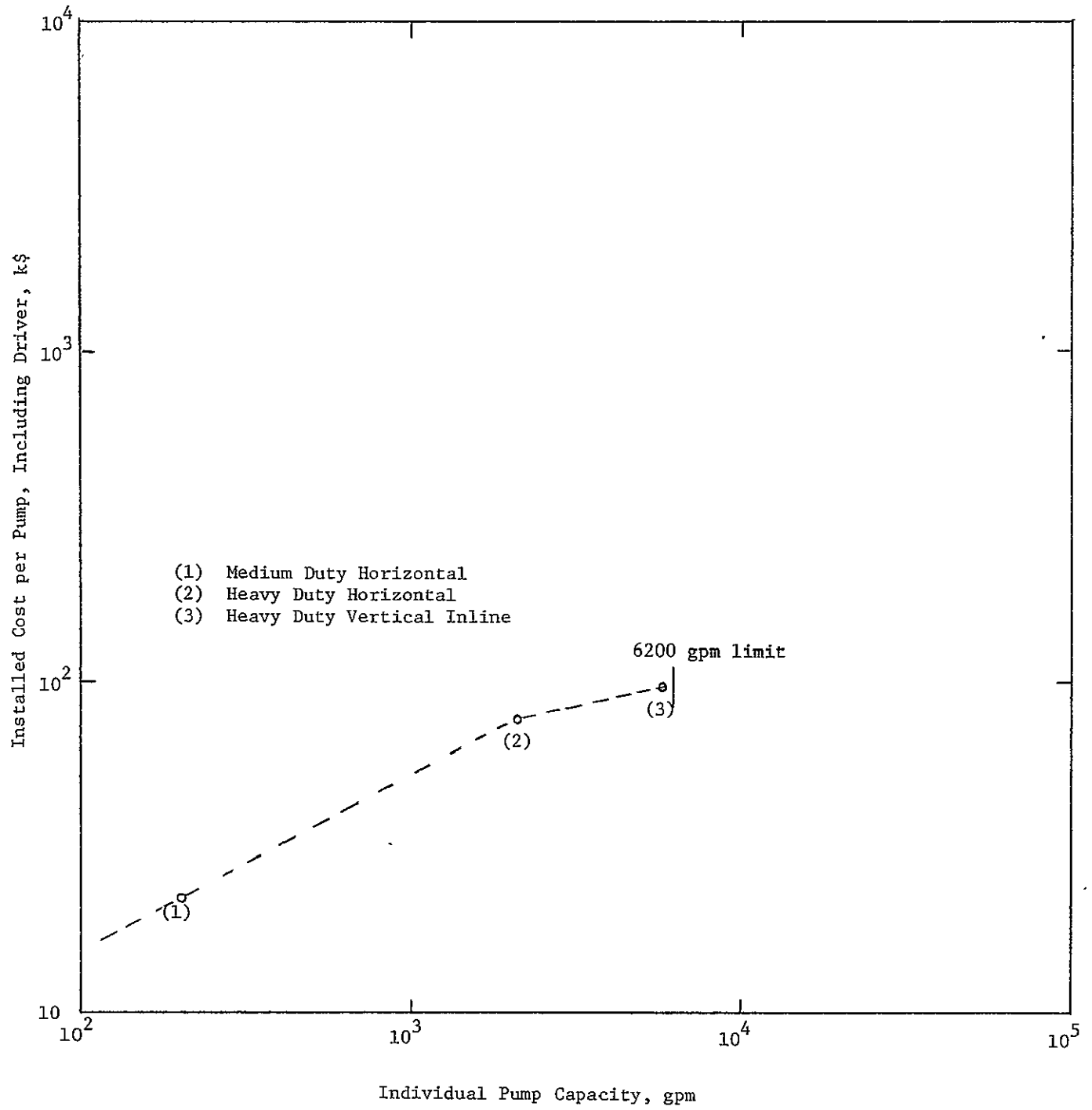
Figure 6Pumping Section Costs

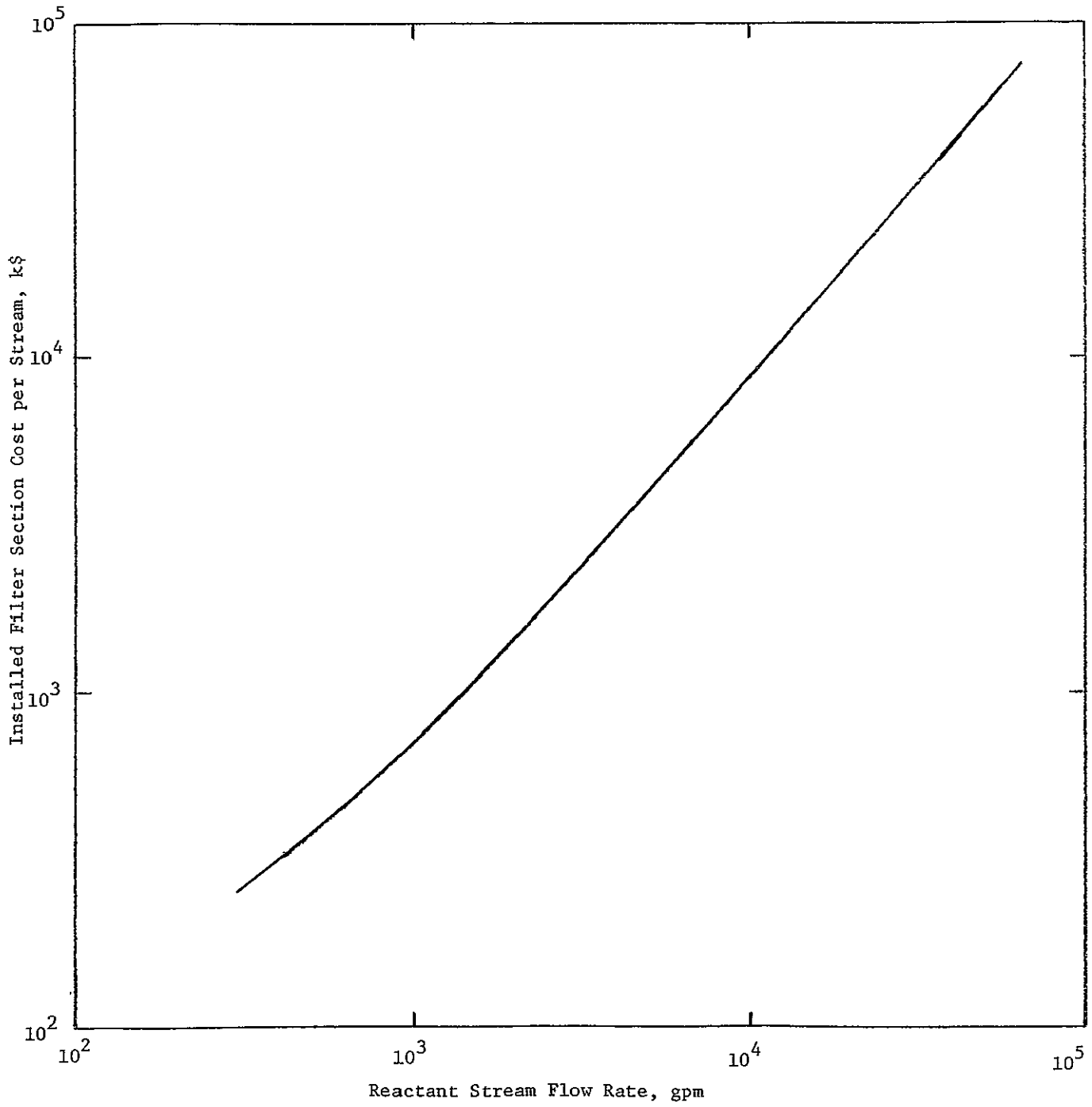
Figure 7Filter Section Costs

Figure 8

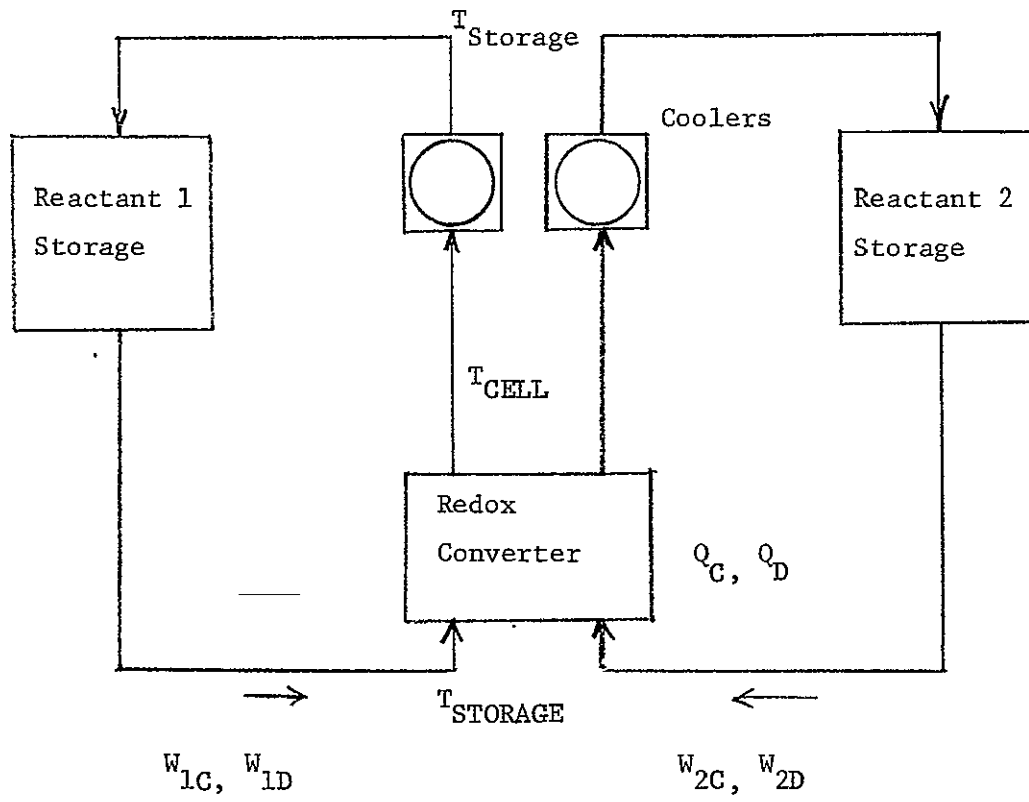
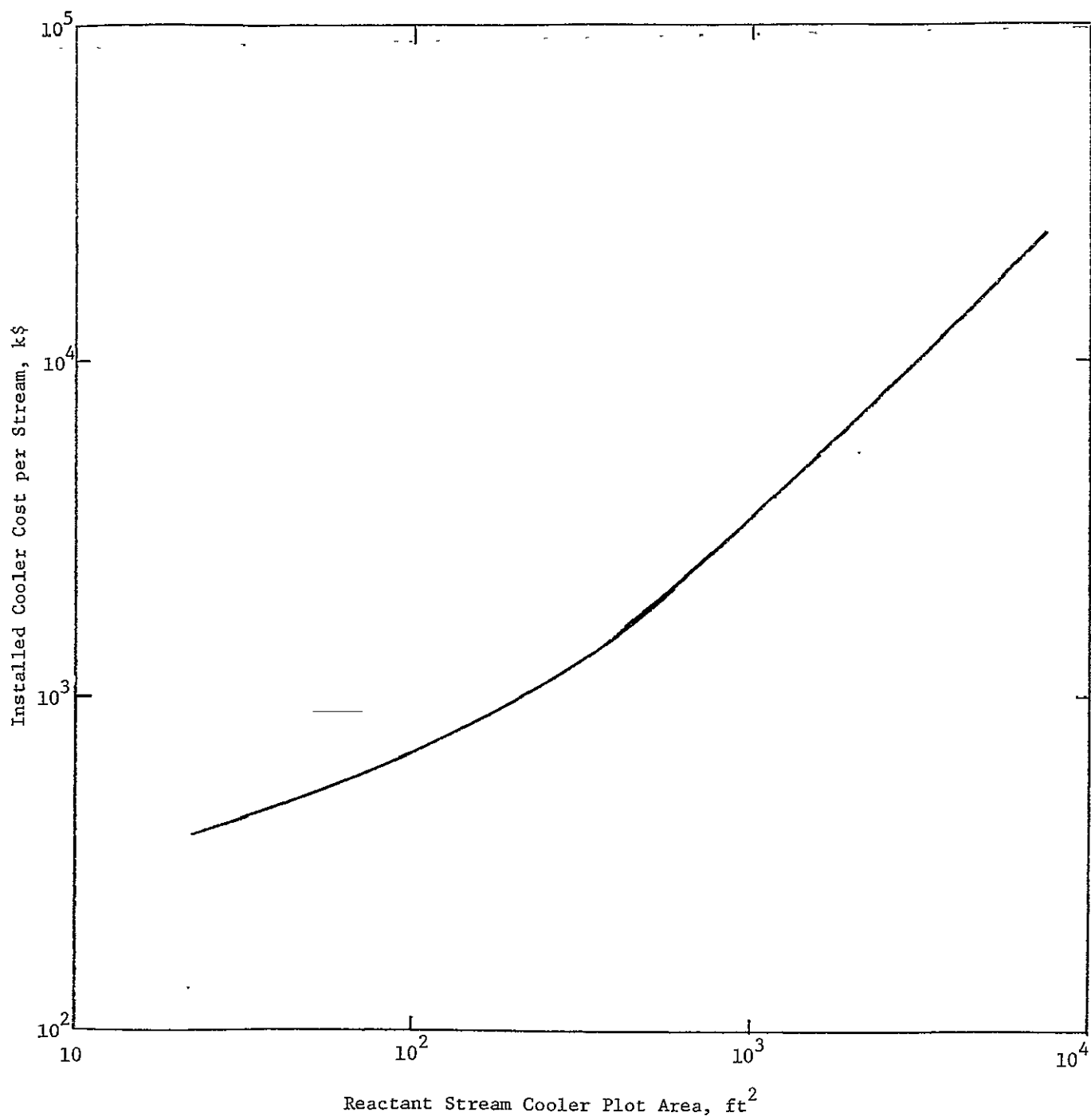
Heat Balance Configuration

Figure 9Cooler Section Costs

ATTACHMENT 1Stage 1 Model Baseline Parameter Recommendations

The Stage 1 System Model provided by NASA contains parameters whose values must be "assumed" or "chosen" by the Model user. Suggested baseline values for these parameters are called for in Task IIIC of our program to study Redox energy storage systems. Table 1 lists the original NASA variables, including:

- Symbol
- Definition
- Computer Program Notation
- Units (Dimensions)
- Recommended Baseline Value
- Suggested Range of Parameter Values

We have also provided the same information for the additional parameters that were introduced to complete the Stage 1 Model. These parameters are covered in Table 2. Further descriptive material on these added parameters is provided in the Stage 1 Model documentation.

Table 1  
Parameters Specified in NASA Stage 1 Model Outline

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
$\epsilon_R$	AC to DC rectifying efficiency	ER	-	0.95	0.9-0.98
$\epsilon_I$	DC to AC inversion efficiency	EI	-	0.95	0.9-0.98
$\epsilon_T$	Cell thermal efficiency	ET	-	1.00	0.8-1.2
$\epsilon_{FC}$	Faradaic cell efficiency during charge	EFC	-	1.00	0.8-1.0
$\epsilon_{FD}$	As above, discharge	EFD	-	1.00	0.8-1.0
$V_c$	Converter charging voltage	CAPVC	volts	500	200-1500
$i_c$	Time-averaged charging current density	IC	amps/cm <sup>2</sup>	0.100	0.01-0.50
$a_C, a_D$	Coefficients in expression for non-ohmic polarization, charge or discharge	AC, AD	volts	0.0	*
$b_C, b_D$	As above	BC, BD	volt cm <sup>2</sup> /amp	0.50	0.0-0.2
$V_R$	Time-averaged reversible cell voltage	VR	volts	0.8	0.4-1.5
$\delta$	Membrane thickness	DELTA	cm	0.010	0.002-0.015
$\rho$	Membrane specific resistivity	RHO	ohm cm	25	10-100

\* Generally, this parameter will = 0, but linear approximations of Tafel equation at high current could yield effective negative values.



Table 1 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
$n_p$	Number of parallel cells	NP	-	**	**
u	Reactant utilization factor	U	-	1.0	0.5-1.0
$f_{1c}, f_{2c}$ $f_{1D}, f_{2D}$	Solution flow rates per cell, charge and discharge for reactants 1 and 2	F1C, F2C F1D, F2D	- -	1.0 1.0	1.0-2.0 1.0-2.0
$MW_1, MW_2$	Reactant molecular wt. (Complete compound basis, i.e., $FeCl_3$ not Fe)	MW1, MW2	gms/gm mole	150	75-250
$Z_1, Z_2$	Electrons transferred per mole	Z1, Z2	eq/gm mole	1	1-3
$C_1, C_2$	Initial concentration of reactants 1 and 2	C1, C2	gm moles/liter	1	1-5
$C_{1S}, C_{2S}$	Supporting electrolyte concentration	C1S, C2S	gm moles/liter	5	1-10

\*\* The Stage 1 Model calculates the cell area using  $n_p$ . In order to keep projected cell size approximately constant as given charging power ( $\mathcal{P}_c$ ) is changed, we recommend using  $n_p \sim 12\mathcal{P}_c$ , where  $\mathcal{P}_c$  is in MW.

Table 2

Additional Parameters Included in Final Stage 1 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
$\bar{\rho}_{\text{SOL}(1)}, \bar{\rho}_{\text{SOL}(2)}$	Average solution density, reactant + electrolyte	RHO1, RHO2	gms/cm <sup>3</sup>	1.05	1-2
$\bar{C}_{\text{P1}}, \bar{C}_{\text{P2}}$	Average solution heat capacity	CP1, CP2	cal/gm°C	0.8	0.7-1.0
$\text{MW}_{\text{SE}}$	Molecular weight of sup- porting electrolyte	MWSE	gms/gm mole	36.4	30-150
$C_{\text{R}(1)}, C_{\text{R}(2)}$	Delivered cost of reactant solutions	CR1, CR2	\$/kg	0.5	0.5-10.0
$C_{\text{SE}}$	Delivered cost of support- ing electrolyte	CSE	\$/kg	0.12	0.1-1.0
$e$	Electrode deposit thickness (on either side of membrane)	EE	cm	0.01	0.005-0.05
$\tau$	Flow channel thickness	TAU	cm	0.05	0.02-0.2
$\gamma_{\text{c}}$	Current collector thickness	GAMMAC	cm	0.60	0.1-0.8
$\gamma_{\text{E}}$	End plate conductor thick- ness	GAMMAE	cm	1.50	1-2
$\rho_{\text{E}}$	Apparent bulk density of electrode deposit	RHOE	gm/cm <sup>3</sup>	0.5	0.4-2.0
$\rho_{\text{cp}}$	Density of cell plastic	RHOCP	gm/cm <sup>3</sup>	0.9	0.8-2.2
$\rho_{\text{cc}}$	Density of current collector material	RHOCC	gm/cm <sup>3</sup>	1.8	1-3

Table 2 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
$\delta_{SW}$	Stack installation clearance, width	DELTSW	cm	30	20-40
$\delta_{SH}$	Same, height	DELTSH	cm	20	10-30
$\delta_{SL}$	Same, length	DELTSL	cm	30	20-40
$T'_H$	Shippable trailer external height	THUS	ft	10	Fixed
$T'_W$	Same, width	TWUS	ft	10	Fixed
$T'_L$	Same, length	TLUS	ft	40	Fixed
$\Delta_T$	Trailer inboard clearance	DELTT	cm	30	20-40
$T_{cell}$	Converter operating temperature	TCELL	°C	50	25-80
$T_{air}$	Ambient air temperature	TAIR	°C	25	5-40
$f_{I(1)}, f_{I(2)}$	Solution inventory factor*	FI1, FI2	-	1.05	1.0-1.1
$f_{TU(1)}, f_{TU(2)}$	Tank ullage factor**	FTU1, FTU2	-	1.1	1.0-1.2
$C_{cp}$	Cost of cell plastic	CCP	\$/kg	0.57	0.5-15
$C_{cc}$	Cost of cell current collector material	CCC	\$/kg	3.30	1-10
$C_E$	Cost of cell electrode deposit	CE	\$/kg	2.20	1-10
$C_M$	Cost of cell membrane	CM	\$/m <sup>2</sup>	9.0	1-20

1-27

\* Ratio,  $\frac{\text{Total solution inventory volume}}{\text{solution inventory for calculated charge}}$

(Accounts for reactant hold-up volume in process equipment and cells.)

\*\* Ratio,  $\frac{\text{Nominal tank volume}}{\text{Nominal liquid content}}$

Table 2 (Continued)

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Baseline Value</u>	<u>Suggested Range of Parameter Values</u>
fm	Stack fabrication cost factor***	FM	-	2.5	2-3
C <sub>TP</sub>	Cost of trailer internal piping	CTP	\$/kw	5	5-15
C <sub>TBB</sub>	Cost of trailer internal busbar + electrical con- nectors	CTBB	\$/kw	10	5-20
C <sub>TS</sub>	Cost of trailer structurals	CTS	\$/kw	5	5-15
C <sub>TI</sub>	Cost of trailer instrumen- tation	CTI	\$/kw	5	5-15
C <sub>I</sub>	Trailer installation cost	CI	\$/kw	20	15-30
C <sub>PCI</sub>	Power conditioner instal- lation cost	CPCI	\$/kw	20	15-30

\*\*\* Ratio, Fabricated stack cost  
Stack material cost

NAS3-19776

ATTACHMENT 2Stage 1 System Model Outline

- 1 - Given      The time-averaged AC charging power  $P_c$   
                  The charging time  $t_c$
- 2 - Assume     The AC to DC rectifying efficiency  $E_R$
- 3 - Then        The stack DC charging power  $P_c$  is given by  
                  
$$P_c = P_c E_R$$
- 4 - Choose     The converter charging voltage  $V_c$
- 5 - Then        The converter charging current  $I_c$  is given by  
                  
$$I_c = P_c / V_c$$
- 6 - Choose     The couples 1 and 2 (e.g., 1 = Fe and 2 = Ti), with  
                  molecular weights  $MW_1$  and  $MW_2$  and electrons  
                  transferred per mole reacted  $Z_1 ; Z_2$
- 7 - Assume     The time-averaged reversible cell voltage  $V_R$   
                  The form and coefficients for an expression giving  
                  the non-ohmic cell polarization  $\Delta V_c$ , e.g.,  
                  
$$\Delta V_c = a_c + b_c i_c$$
  
                  where  $i_c$  is the cell current density
- 8 - Choose     The time-averaged charging current density  $i_c$   
                  The membrane thickness  $\delta$
- 9 - Assume     The membrane specific resistivity  $\rho$  (Ohm-cm)

NAS3-19776

## ATTACHMENT 2

2

10 - Then The time-averaged cell voltage  $v_c$  is given by

$$v_c = v_R + i_c \rho \delta + a_c + b_c i_c$$

The time-averaged cell power density  $p_c$  is given by

$$p_c = v_c i_c$$

The total cell area required  $A$  is given by

$$A = P_c / p_c$$

The number of series cell required  $n_s$  is given by

$$n_s = V_c / v_c$$

11 - Choose The number of parallel cells  $n_p$

12 - Then The total number of cells  $N$  is given by

$$N = n_s n_p$$

The active area per cell  $a \times a$  is given by

$$a \times a = A / N$$

13 - Assume The faradaic cell efficiency  $\epsilon_{fc}$  (presumed the same for both reactants)

14 - Then The rate of generation of reactant 1 (e.g., Fe) in the charged state  $S_{1c}$  is given by

$$S_{1c} = \frac{i_c a \times a \epsilon_{fc} N}{z_1 \mathcal{F}}$$

where  $\mathcal{F}$  is the faradaic constant (amp-sec/eq.)

Similarly

$$S_{2c} = \frac{i_c a \times a \epsilon_{sc} N}{z_2 \mathcal{F}}$$

NAS3-19776

ATTACHMENT 2

3

The total moles of 1 and 2 involved during charge  $M_1$  and  $M_2$  are given by

$$M_1 = S_{1c} t_c$$

$$M_2 = S_{2c} t_c$$

15 - Choose The reactant utilization factor  $u$ , where

$$u = \frac{\text{total moles involved}}{\text{total moles present}}$$

16 - Then The total reactants required  $\mathcal{M}_1$ , and  $\mathcal{M}_2$  are given by

$$\mathcal{M}_1 = M_1 / u$$

$$\mathcal{M}_2 = M_2 / u$$

17 - Choose The initial concentrations of reactants  $C_1$  and  $C_2$  and supporting electrolyte  $C_{1s}$  and  $C_{2s}$  (moles per liter)

18 - Then The volume of solution 1  $V_1$  is given by

$$V_1 = \mathcal{M}_1 / C_1$$

Similarly

$$V_2 = \mathcal{M}_2 / C_2$$

The moles of supporting electrolyte required  $\mathcal{M}_s$  is given by

$$\mathcal{M}_s = V_1 C_{1s} + V_2 C_{2s}$$

NAS3-19776

ATTACHMENT 2

4

19 - Choose The solution flow rates per cell  $f_{1c}$  and  $f_{2c}$   
 (expressed dimensionlessly as the ratio  

$$\frac{\text{moles of reactant in per unit time}}{\text{rate of generation of the charged state of reactant 1}})$$

20 - Then The total reactant flow rates  $w_{1c}$  and  $w_{2c}$   
 are given by

$$w_{1c} = f_{1c} S_{1c}$$

$$w_{2c} = f_{2c} S_{2c}$$

21 - Assume The cell thermal efficiency  $\epsilon_T$  where

$$\epsilon_T = \frac{\Delta F_R}{\Delta H_R} = \frac{\text{free energy of reaction}}{\text{enthalpy of reaction}}$$

22 - Then The waste heat generation rate during charge  $Q_c$   
 (based on the rate of generation of charged  
 species 1) is given by

$$Q_c = Q_c(S_{1c}, \epsilon_{fc}, \epsilon_T, \bar{z}_1, \nu_R, \nu_c)$$

(the actual expression is to be derived by the  
 contractor)\*

23 - Given The discharge period  $t_D$

24 - Then The rate of consumption of reactants in the  
 charged state  $S_{1D}$  and  $S_{2D}$  is given by

$$S_{1D} = M_1 / t_D$$

$$S_{2D} = M_2 / t_D$$

$$* Q_c = \frac{S_{1c} Z_1 F}{\epsilon_{FC}} \left[ v_C - v_R \left( \frac{\epsilon_{FC}}{\epsilon_T} \right) \right]$$



NAS3-19776

ATTACHMENT 2

5

25 - Assume The faradaic efficiency during discharge  $\epsilon_{FD}$

26 - Then The cell current density during discharge  $i_D$

is given by 
$$i_D = \frac{S_{ID} z_1 F \epsilon_{FD}}{a \times a N}$$

27 - Assume The form and coefficients for an expression giving the non-ohmic cell polarization  $\Delta v_D$ , e.g.,  $\Delta v_D = a_D + b_D i_D$

28 - Then The cell discharge voltage  $v_D$  is given by

$$v_D = v_R - i_D \delta_P - a_D - b_D i_D *$$

The discharge power density  $p_D$  is given by

$$p_D = v_D i_D$$

The converter discharge power  $P_D$  is given by

$$P_D = p_D A$$

The waste heat generation rate during discharge  $Q_D$  (based on the rate of consumption of charged species 1) is given by

$$Q_D = S_{ID} \epsilon_{FD} z_1 F \left( \frac{v_R}{\epsilon_{FD} \epsilon_T} - v_D \right)$$

29 - Assume The DC to AC inversion efficiency  $\epsilon_I$

30 - Then The time-averaged discharge power  $\bar{P}_D$  is given

by 
$$\bar{P}_D = P_D \epsilon_I$$

NAS3-19776

ATTACHMENT 2

6

31 - Choose The solution flow rate per cell during discharge  $f_{1D}$  and  $f_{2D}$  (expressed dimensionlessly as in Item 19)

32 - Then The total reactant flow rates  $W_{1D}$  and  $W_{2D}$  are given by

$$W_{1D} = f_{1D} S_{1D}$$

$$W_{2D} = f_{2D} S_{2D}$$

(Details of the calculational approach must be provided by the contractor beyond this point.)

33 - Choose The cell dimensions not specified above (see Fig. 1 for a suggested conceptual design suitable for the stage 1 model).

The cell materials and densities  
 The cell materials' specific costs

34 - Then The amounts of material required for the converter and converter costs may be calculated.

35 - Assume The specific costs of solution components (reactant 1, reactant 2, supporting electrolyte)

36 - Then The solution costs may be calculated

37 - Assume The amount of piping required

The specific piping cost

38 - Then The cost of piping may be calculated

The total volume of piping may be calculated for each solution

The amount of solution in each tank may be calculated

NAS3-19776

## ATTACHMENT 2

- 39 - Choose      The tank configurations  
                 The percent ullage for each tank
- 40 - Then        The tank size may be calculated .
- 41 - Choose      The tank material
- 42 - Then        The tank cost may be calculated
- 43 - Choose      The pump types and sizes (according to the  
                 larger of the two flow rates)
- 44 - Then        The pump costs may be calculated
- 45 - Choose      The heat exchanger design
- 46 - Then        The sizes and costs of the heat exchangers  
                 may be calculated
- 47 - Choose      The filter configurations
- 48 - Then        The filter sizes and costs may be calculated
- 49 - Choose      The wiring configuration
- 50 - Then        The amounts and costs of conductors may be calculated
- 51 - Choose      The types and sizes of power processing equipment
- 52 - Then        The power processing costs may be calculated
- 53 - Assume      A multiplier for instrumentation and controls costs  
                 (i.e., i. and c. costs equals some fraction of  
                 total hardware costs)
- 54 - Assume      A multiplier for installation and miscellaneous  
                 costs

NAS3-19776

ATTACHMENT 2

8

55 - Then            The total system installed cost is given by

TOTAL INSTALLED COST =

converter cost

+ piping 1 cost + piping 2 cost

+ tank 1 cost + tank 2 cost

+ pump 1 cost + pump 2 cost

+ filter 1 cost + filter 2 cost

+ hx 1 cost + hx 2 cost

+ solution 1 cost + solution 2 cost

+ wiring cost

+ power processing costs

+ instrumentation costs

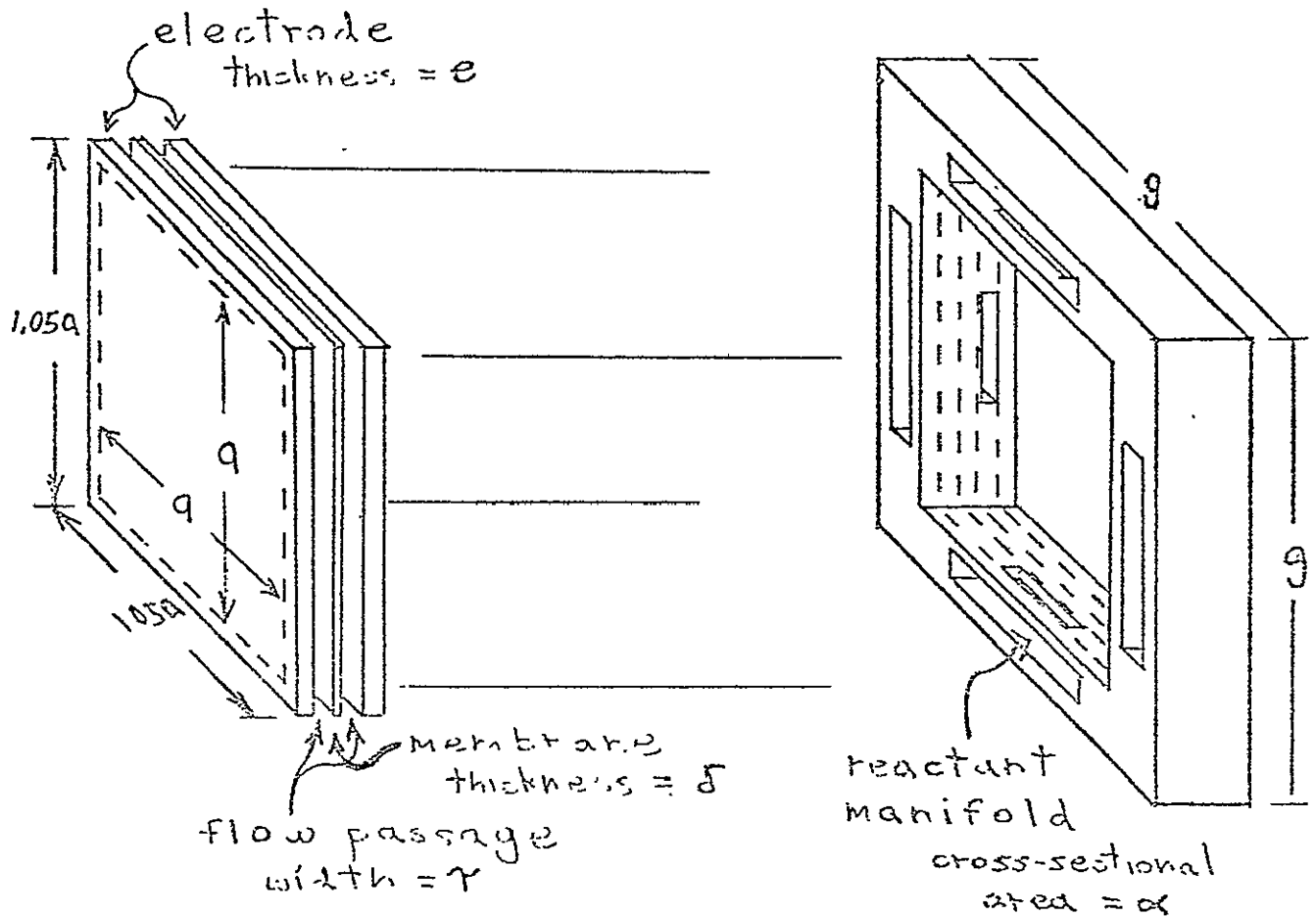
+ installment and miscellaneous costs

NAS3-19776

ATTACHMENT 2

9

Fig. 1 - Conceptual Cell Design for Stage 1 Model



cell component active area =  $a \times a$

cell component total area =  $1.05a \times 1.05a \approx 1.1a^2$

frame thickness =  $\delta + 2\gamma + 2e$

fluid filled volume per fluid per cell

$$\approx a \times a f + 2\alpha(\delta + 2\gamma + 2e)$$

# **EXXON** RESEARCH AND ENGINEERING COMPANY

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GOVERNMENT RESEARCH LABORATORIES

## REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

Task IIIA

Documentation for Stage 1.5  
Model Computer Program

By

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December 20, 1976

**government  
research**

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## Table of Contents

Introduction . . . . .	1
Input Descriptions . . . . .	1A
Input Format	
Card Structure	
Base Case Data	
Parametric Case Data	
Case Delimiter Card	
Error Handling	
Card Input Instructions. . . . .	5
Program Structure. . . . .	64
Overall Structure	
Input Phase	
Electrochemical Calculation Phase	
Economic Calculation Phase	
Output Phase	
Subroutine Descriptions. . . . .	66

Storage Battery Program ( Model 1.5)

Program Documentation

December 1976



## INTRODUCTION

The following is a brief description of the logic and operational features of the Stage 1.5 Model of Redox Energy Storage Systems. This model can analyze weekly storage cycles. The remaining sections of this documentation package provide additional details of the computer program software. The basic equations used to characterize the Redox system are identical to those used in the Stage 1 Model, given in Appendix 1 of the Stage 1 Model documentation package.

Model 1 was a daily cycle calculation and the program manipulated one of the power variables in order to return the system to the original reactant inventory starting point. Model 1.5 is a weekly cycle calculation and the program manipulates the charging times in order to return the system to the original starting point. There are two ways this manipulation can be performed, depending on the program user's choice. One is that the solutions, at any point in the cycle cannot exceed the original (Monday morning) charge. The second way permits overcharging during the initial days of the weekly cycle, a possible advantage for asymmetric energy demand profiles.

The user provides a charge time/discharge time schedule and charge/discharge power levels. The latter are assumed constant during the week. The program calculates the minimum possible energy storage efficiency that can satisfy the designated schedule (using all available charge time). If this is less than the maximum possible electrochemical efficiency (calculated from the input parameters), the program continues, otherwise it stops.

The program calculates the daily inventory for both reactants before and after each discharge and charge period. In all cases, there will be at least one point when the solutions are fully discharged.

### M Determination

The program calculates the values of S1C, S2C, SID, S2D and sets  $M_1$  and  $M_2$  equal to zero. The program then begins the cycle calculations by calculating the amount of material consumed (discharged) and subtracts it from  $M_i$  (yielding a negative number). Then it calculates the amount recharged during the charge cycle and adds it to  $M_i$  but  $M_i$ ,  $i=1,2$  is not allowed to go positive in the first program option. If so, the charge time is reduced to maintain  $M_i$  at zero. When the cycle calculations are completed, the value of M is obtained by taking the absolute value of the largest negative value of M to occur during the cycle.

In the second program operating option, overcharging is permitted early in the week. The program logic is arranged to survey the discharge demand later in the week and to adjust the extent of overcharge to develop an energy-balanced cycle. Again, the value of M is normalized. As before, M will drop to zero at some point in the cycle.

### $i_C$ Manipulation

The charging current density,  $i_C$ , can be changed during program operation in order to satisfy the objectives listed below:

- Optimization -  $i_C$  is varied in order to minimize either the power costs, \$/kW, or the energy cost, \$/kwh.
- Cycle Feasibility -  $i_C$  is reduced, if needed, such that the user inputted charge/discharge cycle can restore the system to the original level of charge.
- $i_D$  Feasibility -  $i_C$  is reduced, if needed, to insure that a valid  $i_D$  can be calculated.

### Optimization

The program searches values of  $i_C$  until it bounds the region of minimum cost (power or energy). It then uses a golden section search to reduce this region until two neighboring values of  $i_C$  produce a system with the number of trailers differing by one.

Analysis of weekly cycle operation using the Stage 1.5 Model is presented in Volume 1 of this final report.

## Input Description

### Input Format

The input to the Storage Battery Program( Model 1.5 ) consists of a series of cases. A case consists of a base case and any number of parametric cases.

#### Base Case

A base case consists of all the input data required by the program to do the calculations.

#### Parametric Case

A parametric case contains only that information that differs from the base case. The changes indicated by parametric cases are accumulative such that parametric case number four, say, modifies parametric case number three and not the base case. In other words, the user must reset all data to base case conditions, if so desired, because the program will not.

### Card Structure

Each input card consists of eight fields of ten columns each. The first field contains an unique keyword which describes the data on the card. Depending on the keyword, the remaining data on the card will be in the next one to seven fields.

## Keywords

The allowable keywords are:

CELL	ELECTRANS
CELLCOST	HTCAPACITY
CELLDENSTY	MEMBRANE
CELLSIZE	MOLEWEIGHT
CHARGE	POWER
CHRGFLOW	POWERCOND
CYCLETEC	REACCONC
CYCLETD	SOLNCOST
DENSITY	STACKSIZE
DHRGFLOW	TEMP
DISCHARGE	TRALRCOST
EFFICIENCY	TRALRSIZE
ELECCONC	ULLAGE
*CONTROL	
*END	
*OPTIONS	
*PARA	
*TITLE	

## Base Case Data

The program sets all input variables to zero before each base case. Therefore, any input variable that is not specified will have the value of 0.0.

## Parametric Case Data

The user need supply only that data which differs from the previous case ( base case or parametric ) because the program only updates the non-zero entries on a card. If no data on a certain keyword card changes then the user need not supply that card. Also, if the user wants to zero out a number he must enter a suitably small number, e.g. 0.0001, because the program cannot distinguish between a blank field, which it sets to 0.0, and a valid 0.0 entry.

## Case Delimiter Cards

The user indicates that the data is complete for one set of calculations by supplying either a \*END or a \*PARAM card after the data.

### \*END Card

A \*END card indicates that the preceding data is complete and denotes the end of a case. Therefore, upon returning to the input phase, the program will recognize the next cards as a new base case and will re-initialize all input variables to zero.

### \*PARAM Card

A \*PARAM card indicates that the preceding data is complete and that additional parametric cases will follow. Therefore, upon returning to the input phase, the program will process the following cards as a parametric case and only change the non-zero data values that are entered.

## Error Handling

The program tries to anticipate common input errors and take the appropriate action before proceeding further.

### Input Processing

A misspelled keyword renders the rest of that case's data useless; but rather than flush the input cards to the first \*END card ( new base case ) the program will continue to process the input data looking for more possible errors. In this way, most errors can be found at once rather than one at a time.

Also, the program checks for those variables and variable combinations that are used as divisors in the electro-chemical equations to insure that a zero divisor does not result. If so, these variables are printed out and the program remains in the input phase until that condition no longer exists or a \*END card is read.

### Calculation Phase

In the electro-chemical calculations the program constantly checks for those variables or variable combinations that would result in a zero divisor. If any are detected, the program prints out the expression for the user's information and returns to the input phase.

### Card Input Instructions

The next pages describe the input forms and how to fill them out. An example form will be on the facing page as an easy reference for the user. The input cards are described in alphabetical order to provide the user with a convenient reference tool. The user should be reminded that the input cards can be submitted in any order with only two exceptions ( Case Delimiter and Title Cards)

As a programming aid, the FORTRAN variable name used in the program is listed with each variable description along with the column numbers of its field on the card.

CELL CARD

										CELL VOLTAGE (volts)										NUMBER OF PARALLEL CELLS										REACTANT UTILIZATION FACTOR																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL																																																																															



Cell Card

Cell Voltage ( VR )  
cc. 11-20

Enter the assumed  
time-averaged reversible cell  
voltage.  
( volts )

Parallel Cells ( NP )  
cc. 21-30

Enter the number of parallel  
cells.  
( - )

Reactant Utilization Factor ( U )  
cc. 31-40

Enter the reactant utilization  
factor U, where:

$$u = \frac{\text{total moles involved}}{\text{total moles present}}$$

( - )

### CELL COST CARD

										PLASTIC (\$/kg)										CURRENT COLLECTOR (\$/kg)										ELECTRODE DEPOSIT (\$/kg)										MEMBRANE (\$/m <sup>2</sup> )										STACK FACTOR																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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Cell Cost Card

Plastic Cost ( CCP )  
cc. 11-20

Enter the cost of the cell  
plastic.  
( \$/kg )

Collector Cost ( CCC )  
cc. 21-30

Enter the cost of the current  
collector material.  
( \$/kg )

Electrode Cost ( CE )  
cc. 31-40

Enter the cost of the  
electrode deposit.  
( \$/kg )

Membrane Cost ( CM )  
cc. 41-50

Enter the cost of the membrane  
material.  
( \$/kg )

Stack Factor ( FM )  
cc. 51-60

Enter the ratio of the stack  
manufactured cost to the stack  
materials cost. Normal range  
is probably in the  
neighborhood of 2-3.  
( - )

## CELL DENSITY CARD

										PLASTIC (gm/cm <sup>3</sup> )										CURRENT COLLECTOR (gm/cm <sup>3</sup> )										ELECTRODE DEPOSIT (gm/cm <sup>3</sup> )																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL DENSITY																																																																															

Cell Density Card

Cell Plastic Density ( RHOCP )  
cc. 11-20

Enter the density of the cell  
plastic material used in the  
cell.  
( gm/cm<sup>3</sup> )

Current Collector Density ( RHOCC )  
cc. 21-30

Enter the density of the  
current collector material.  
( gm/cm<sup>3</sup> )

Electrode Deposit Density ( RHOE )  
cc. 31-40

Enter the apparent bulk  
density of the electrode  
deposit.  
( gm/cm<sup>3</sup> )

Membrane Density ( RHOM )  
cc. 41-50

Enter the density of the cell  
membrane.  
( gm/cm<sup>3</sup> )

CELL SIZE CARD

										ELECTRODE THICKNESS (cm)										FLOW CHANNEL THICKNESS (cm)										CURRENT COLLECTOR THICKNESS (cm)										END PLATE CONDUCTOR THICKNESS (cm)																																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CELL SIZE																																																																															

Cell Size Card

Electrode Thickness ( EE )  
cc. 11-20

Enter the electrode thickness.  
( cm )

Flow Channel Thickness ( TAU )  
cc. 21-30

Enter the thickness of the  
flow channel. It is the same  
for each reactant.  
( cm ).

Current Collector Thickness ( GAMMAC )  
cc. 31-40

Enter the thickness of the  
current collector for the  
interior portion of the cell.  
( cm. )

End Plate Conductor Thickness ( GAMMAE )  
cc. 41-50

Enter the thickness of the  
conductor on each end plate.  
( cm. )

CHARGE CARD

										CURRENT DENSITY  (amp/cm <sup>2</sup> )	NON-OHMIC CELL POLARIZATION										CONVERTER CHARGING VOLTAGE  (volts)																																																										
											INTERCEPT					SLOPE																																																															
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CHARGE																																																																															



Charge Card

Current Density ( IC )  
cc. 11-20

Enter the cell current density  
during charge.  
( amp/cm<sup>2</sup> )

Coefficient ( AC )  
cc. 21-30

Enter the intercept for the  
non-ohmic cell polarization  
equation during charge.  
( volts )

Coefficient ( BC )  
cc. 31-40

Enter the slope coefficient  
for the non-ohmic cell  
polarization equation during  
charge.  
( v.cm<sup>2</sup>/amp )

Converter Charging Voltage (CAPVC )  
cc. 41-50

Enter the converter charging  
voltage.  
( volts )

# CHARGE FLOW CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
CHRG FLOW																																																																															

## Charge Flow Card

Reactant 1 ( F1C )  
cc. 11-20

Enter the solution flow rate  
per cell for reactant 1 during  
charge as:

$$f1c = \frac{\text{moles of reactant per unit time}}{\text{rate of generation of the charged state of reactant}}$$

( - )

Reactant 2 ( F2C )  
cc. 21-30

Enter the solution flow rate  
per cell for reactant 2 during  
charge as:

$$f2c = \frac{\text{moles of reactant per unit time}}{\text{rate of generation of the charged state of reactant}}$$

{ - )

### CHARGE CYCLE TIMES

	Enter available time for charge (hours)																																																																														
	Monday								Tuesday								Wednesday								Thursday								Friday								Saturday								Sunday																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79
C.V.C. L E T C																																																																															

Cycletc Card

Monday Charge Time  
cc 11-20

Enter the available time for  
charge on Monday.  
( hours )

Tuesday Charge Time  
cc 21-30

Enter the available time for  
charge on Tuesday.  
( hours )

Wednesday Charge Time  
cc 31-40

Enter the available time for  
charge on Wednesday.  
( hours )

Thursday Charge Time  
cc 41-50

Enter the available time for  
charge on Thursday.  
( hours )

Friday Charge Time  
cc 51-60

Enter the available time for  
charge on Friday.  
( hours )

Saturday Charge Time  
cc 61-70

Enter the available time for  
charge on Saturday.  
( hours )

Sunday Charge Time  
cc 71-80

Enter the available time for  
charge on Sunday.  
( hours )

### DISCHARGE CYCLE TIMES

[illegible]

Cycletd Card

Monday Discharge Time  
cc 11-20

Enter the available time for  
discharge on Monday.  
( hours )

Tuesday Discharge Time  
cc 21-30

Enter the available time for  
discharge on Tuesday.  
( hours )

Wednesday Discharge Time  
cc 31-40

Enter the available time for  
discharge on Wednesday.  
( hours )

Thursday Discharge Time  
cc 41-50

Enter the available time for  
discharge on Thursday.  
( hours )

Friday Discharge Time  
cc 51-60

Enter the available time for  
discharge on Friday.  
( hours )

Saturday Discharge Time  
cc 61-70

Enter the available time for  
discharge on Saturday.  
( hours )

Sunday Discharge Time  
cc 71-80

Enter the available time for  
discharge on Sunday.  
( hours )

# DENSITY CARD

										REACTANT 1 (gm/cm <sup>3</sup> )										REACTANT 2 (gm/cm <sup>3</sup> )																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
DENSITY																																																																															



Density Card

Reactant 1 Density ( RHO1 )  
cc. 11-20

Enter the average solution  
density( reactant and  
supporting electrolyte) for  
reactant 1 solution.  
( gm/cm3 )

Reactant 2 Density ( RHO2 )  
cc. 21-30

Enter the average solution  
density( reactant and  
supporting electrolyte) for  
reactant 2 solution.  
( gm/cm3 )

# DISCHARGE CARD

																				NON-OHMIC CELL POLARIZATION																																																											
																				intercept																														slope																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
DISCHARGE																																																																															

Discharge Card

cc. 11-20

\*\*\*EMPTY FIELD\*\*\*

Coefficient { AD }  
cc. 21-30

Enter the intercept for the  
non-ohmic cell polarization  
equation during discharge.  
( volts )

Coefficient { BD }  
cc. 31-40

Enter the slope coefficient  
for the non-ohmic cell  
polarization equation during  
discharge.  
( v.cm<sup>2</sup>/amp )

DISCHARGE FLOW CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
D.H.R.G.FLOW																																																																															

## Discharge Flow Card

Reactant 1 ( F1D )  
cc. 11-20

Enter the solution flow rate  
per cell for reactant 1 during  
discharge as:

moles of reactant per  
unit time  
f1d = -----  
rate of generation of the  
discharged state of  
reactant

( - )

Reactant 2 ( F2D )  
cc. 21-30

Enter the solution flow rate  
per cell for reactant 2 during  
discharge as:

moles of reactant per  
unit time  
f2d = -----  
rate of generation of the  
discharged  
state of reactant

( - )

# EFFICIENCY CARD

	RECTIFICATION	INVERSION	THERMAL	Faradaic		
				charge	discharge	
1	11	21	31	41	51	61
2	12	22	32	42	52	62
3	13	23	33	43	53	63
4	14	24	34	44	54	64
5	15	25	35	45	55	65
6	16	26	36	46	56	66
7	17	27	37	47	57	67
8	18	28	38	48	58	68
9	19	29	39	49	59	69
10	20	30	40	50	60	70
11	31	41	51	61	71	81
12	32	42	52	62	72	82
13	33	43	53	63	73	83
14	34	44	54	64	74	84
15	35	45	55	65	75	85
16	36	46	56	66	76	86
17	37	47	57	67	77	87
18	38	48	58	68	78	88
19	39	49	59	69	79	89
20	40	50	60	70	80	90
21	51	61	71	81	91	01
22	52	62	72	82	92	02
23	53	63	73	83	93	03
24	54	64	74	84	94	04
25	55	65	75	85	95	05
26	56	66	76	86	96	06
27	57	67	77	87	97	07
28	58	68	78	88	98	08
29	59	69	79	89	99	09
30	60	70	80	90	00	10
31	71	81	91	01	11	21
32	72	82	92	02	12	22
33	73	83	93	03	13	23
34	74	84	94	04	14	24
35	75	85	95	05	15	25
36	76	86	96	06	16	26
37	77	87	97	07	17	27
38	78	88	98	08	18	28
39	79	89	99	09	19	29
40	80	90	00	10	20	30
41	91	01	11	21	31	41
42	92	02	12	22	32	42
43	93	03	13	23	33	43
44	94	04	14	24	34	44
45	95	05	15	25	35	45
46	96	06	16	26	36	46
47	97	07	17	27	37	47
48	98	08	18	28	38	48
49	99	09	19	29	39	49
50	00	10	20	30	40	50
51	01	11	21	31	41	51
52	02	12	22	32	42	52
53	03	13	23	33	43	53
54	04	14	24	34	44	54
55	05	15	25	35	45	55
56	06	16	26	36	46	56
57	07	17	27	37	47	57
58	08	18	28	38	48	58
59	09	19	29	39	49	59
60	10	20	30	40	50	60
61	11	21	31	41	51	61
62	12	22	32	42	52	62
63	13	23	33	43	53	63
64	14	24	34	44	54	64
65	15	25	35	45	55	65
66	16	26	36	46	56	66
67	17	27	37	47	57	67
68	18	28	38	48	58	68
69	19	29	39	49	59	69
70	20	30	40	50	60	70
71	21	31	41	51	61	71
72	22	32	42	52	62	72
73	23	33	43	53	63	73
74	24	34	44	54	64	74
75	25	35	45	55	65	75
76	26	36	46	56	66	76
77	27	37	47	57	67	77
78	28	38	48	58	68	78
79	29	39	49	59	69	79
80	30	40	50	60	70	80
81	31	41	51	61	71	81
82	32	42	52	62	72	82
83	33	43	53	63	73	83
84	34	44	54	64	74	84
85	35	45	55	65	75	85
86	36	46	56	66	76	86
87	37	47	57	67	77	87
88	38	48	58	68	78	88
89	39	49	59	69	79	89
90	40	50	60	70	80	90
91	41	51	61	71	81	91
92	42	52	62	72	82	92
93	43	53	63	73	83	93
94	44	54	64	74	84	94
95	45	55	65	75	85	95
96	46	56	66	76	86	96
97	47	57	67	77	87	97
98	48	58	68	78	88	98
99	49	59	69	79	89	99
00	50	60	70	80	90	00

## Efficiency Card

Rectifying Efficiency ( ER )  
cc. 11-20

Enter the AC to DC rectifying  
efficiency factor.  
(  $0 < ER < 1$  )

Inversion Efficiency ( EI )  
cc. 21-30

Enter the DC to AC inversion  
efficiency factor.  
(  $0 < EI < 1$  )

Thermal Efficiency ( ET )  
cc. 31-40

Enter the cell thermal  
efficiency factor as the ratio  
of the free energy of reaction  
to the enthalpy of reaction.  
(  $0 < ET < 1$  )

Faradaic Cell Efficiency ( EFC )  
cc. 41-50

Enter the Faradaic cell  
efficiency factor during  
charge.  
(  $0 < EFC < 1$  )

Faradaic Cell Efficiency ( EFD )  
cc. 51-60

Enter the Faradaic cell  
efficiency factor during  
discharge.  
(  $0 < EFD < 1$  )

ELECTROLYTE CONCENTRATION CARD

										SOLUTION 1 (moles/l.)										SOLUTION 2 (moles/l.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ELEC CONC																																																																															



Electrolyte Concentration Card

Solution 1 ( C1S )  
cc. 11-20

Enter the initial  
concentration of supporting  
electrolyte in solution 1.  
( moles/litre )

Solution 2 ( C2S )  
cc. 21-30

Enter the initial  
concentration of supporting  
electrolyte in solution 2.  
( moles/litre )

5-7

ELECTRONS TRANSFERRED CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ELECTRONS																																																																															

Electrons Transferred Card

Reactant 1 ( Z1 )  
cc. 11-20

Enter the electrons  
transferred per mole of  
reactant 1.  
( eq/mole )

Reactant 2 ( Z1 )  
cc. 21-30

Enter the electrons  
transferred per mole of  
reactant 2.  
( eq/mole )

## HEAT CAPACITY CARD

										REACTANT 1										REACTANT 2																																																											
										(cal/gm.deg C.)										(cal/gm.deg C.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
H.T. CAPACITY																																																																															

# Heat Capacity Card

Reactant 1 Heat Capacity ( CP1 )  
cc. 11-20

Enter the average solution  
heat capacity( reactant and  
supporting electrolyte) for  
reactant 1 solution.  
( cal/gm.deg C )

Reactant 2 Heat Capacity ( CP2 )  
cc. 21-30

Enter the average solution  
heat capacity( reactant and  
supporting electrolyte) for  
reactant 2 solution.  
( cal/gm.deg C )

MEMBRANE CARD

										THICKNESS (cm)										RESISTIVITY (ohm.cm)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
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Membrane Card

Thickness ( DELTA )  
cc. 11-20

.Enter the membrane thickness.  
( cm )

Resistivity ( RHO )  
cc. 21-30

Enter the membrane specific  
resistivity.  
( ohm.cm )

MOLECULAR WEIGHT CARD

										REACTANT 1										REACTANT 2																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
M.O. LEWELIGHT																																																																															



Molecular Weight Card

Reactant 1 ( MW1 )  
cc. 11-20

Enter the molecular weight of  
reactant 1.  
( - )

Reactant 2 ( MW2 )  
cc. 21-30

Enter the molecular weight of  
reactant 2.  
( - )

POWER CARD

	CHARGE										DISCHARGE																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
	POWER (mw)					TIME (hours)					POWER (mw)					TIME (hours)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
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Power Card

Charge Power ( SCRPC )  
cc. 11-20

Enter the time averaged  
charging power.  
( mw )

Charge Time ( TC )  
cc. 21-30

Enter the charging time.  
( hours )

Discharge Power ( SCRPD )  
cc. 31-40

Enter the time averaged  
discharge power.  
( mw )

Discharge Time ( TD )  
cc. 41-50

Enter the discharging time.  
( hours )

Note:

Three of these four variables must be entered and the program will calculate the fourth. If all four are specified, the program will default to calculate the discharge power if it is a base case. For a parametric case the program will solve for the quantity it solved for in the previous case; however, the user can override this by putting a '-1' in the field corresponding to the desired unknown variable. If the weekly option is chosen, values for TC and TD need not be entered.

POWER CONDITIONING CARD

										POWER CONDITIONING COST (\$/kw)																																																																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
POWERCOND																																																																															

Power Conditioning Card

Power Conditioning Cost { CPCI }  
cc. 11-20

Enter the power conditioning  
installation cost.  
( \$/kw )

REACTANT CONCENTRATION CARD

										REACTANT 1										REACTANT 2																																																											
										(moles/l.)										(moles/l.)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
REACCONS																																																																															

Reactant Concentration Card

Reactant 1 ( C1 )  
cc. 11-20

Enter the initial  
concentration of reactant 1.  
( moles/litre )

Reactant 2 ( C2 )  
cc. 21-30

Enter the initial  
concentration of reactant 2.  
( moles/litre )

SOLUTION COST CARD

										REACTANT 1 (\$/kg)	REACTANT 2 (\$/kg)	SUPPORTING ELECTROLYTE																																																																			
												cost (\$/kg)	molecular weight																																																																		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
SOLN COST																																																																															



Solution Cost Card

Reactant 1 ( CR1 )  
cc. 11-20

Enter the cost of reactant 1  
in solution form.  
( \$/kg )

Reactant 2 ( CR2 )  
cc. 21-30

Enter the cost of reactant 2  
in solution form.  
( \$/kg )

Supporting electrolyte ( CSE )  
cc. 31-40

Enter the cost of the  
supporting electrolyte.  
( \$/kg )

Molecular weight ( MWSE )  
cc. 41-50

Enter the molecular weight of  
the supporting electrolyte.  
( - )

# STACK SIZE CARD

	STACK INSTALLATION CLEARANCE			
	WIDTH (cm)	HEIGHT (cm)	LENGTH (cm)	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80				
STACK SIZE				

Stack Size Card

Width { DELTSW }  
cc. 11-20

Enter the stack installation  
clearance, width.  
( cm )

Height { DELTSH }  
cc. 21-30

Enter the stack installation  
clearance, height.  
( cm )

Length { DELTSL }  
cc. 31-40

Enter the stack installation  
clearance, length.  
( cm )

# TEMPERATURE CARD

										CELL TEMPERATURE (°C)										AMBIENT TEMPERATURE (°C)																																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
TEMP																																																																															

Temperatures Card

Cell Temperature ( TCELL )  
cc. 11-20

Enter the average cell  
temperature.  
( deg. C )

Ambient Temperature (TAIR )  
cc. 21-30

Enter the average ambient  
temperature.  
( deg. C )

TRAILER COST CARD

	PIPING (\$/kw)									BUSBAR (\$/kw)									STRUCTURALS (\$/kw)									INSTRUMENTATION (\$/kw)									INSTALLATION (\$/kw)																																											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	
TRIAL COST.																																																																																

Trailer Cost Card

Piping Cost ( CTP )  
cc. 11-20

Enter the trailer internal  
piping cost.  
( \$/kw )

Busbar Cost ( CTBB )  
cc. 21-30

Enter the trailer internal  
busbar and electrical  
connector cost.  
( \$/kw )

Structurals Cost ( CTS )  
cc. 31-40

Enter the trailer internal  
structurals cost.  
( \$/kw )

Instrumentaion Cost ( CTI )  
cc. 41-50

Enter the trailer internal  
instrumentaion cost.  
( \$/kw )

Installation Cost ( CI )  
cc. 51-60

Enter the trailer installation  
cost.  
( \$/kw )

ULLAGE CARD

[illegible]



Trailer Size Card

Height ( THUS )  
cc. 11-20

Enter the external height of a  
shippable trailer.  
( feet )

Width ( TWUS )  
cc. 21-30

Enter the external width of a  
shippable trailer.  
( feet ).

Length ( TLUS )  
cc. 31-40

Enter the external length of a  
shippable trailer.  
( feet )

Trailer Clearance ( DELTT )  
cc. 41-50

Enter the inboard clearance in  
a shippable trailer.  
( cm )

TRAILER SIZE CARD

	SHIPPABLE TRAILER EXTERNAL DIMENSIONS			INBOARD CLEARANCE (cm)	
	HEIGHT (feet)	WIDTH (feet)	LENGTH (feet)		
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80					
TRAILER SIZE					

Ullage Card

Reactant 1 ( FT1 )  
cc. 11-20

Enter the solution 1 inventory  
factor.  
( - )

Reactant 2 (FT2)  
cc. 21-30

Enter the solution 2 inventory  
factor.  
( - )

Reactant 1 Tank ( FTU1 )  
cc. 31-40

Enter the ullage factor for  
the tank holding reactant 1.  
( - )

Reactant 2 Tank ( FTU2 )  
cc. 41-50

Enter the ullage factor for  
the tank holding reactant 2.  
( - )

\*CONTROL CARD

										OUT1										OUT2										OUT 3																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
*CONTROL																																																																															

\*Control Card  
Output Suppression

Out1  
cc 11-20

Enter a 1.0 to suppress the electrochemical data report. Enter a 0.1 to re-instate this report if it was suppressed in a previous case. If left blank, report will appear for each case.

Out2  
cc 21-30

Enter a 1.0 to suppress the economic summary report. Enter a .0.1 to re-instate this report if it was suppressed in a previous case. If left blank, report will appear for each case.

Out3  
cc 31-40

Enter a 1.0 to suppress the detailed equipment cost report. Enter a 0.1 to re-instate this report if it was suppressed in a previous case. If left blank, report will appear for each case.

## \*OPTIONS CARD

										Cycle										Calculation										Optimization Criterion										Efficiency Criterion										Charge																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															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\*OPTIONS card

Cycle Option  
cc 11-20

0. = daily, Enter TC and TD on  
POWER.  
1. = weekly, Enter TC and TD  
on CYCLETC and CYCLETD cards.  
0.1= { re-instates daily  
option ).

Calculation Option  
cc 21-30

0. = simulation, Enter value  
of IC on CHARGE card.  
1. = optimization, Enter  
estimate of IC on CHARGE card.  
0.1 = { re-instates simulation  
option ).

Optimization Criterion  
cc 31-40

0. = power cost, Program will  
minimize \$/kw.  
1. = energy cost, Program will  
minimize \$/kwh.  
0.1 = { re-instates power cost  
option ).

Efficiency Criterion (TOLEFF)  
cc 41-50

program will terminate any  
weekly case with a larger  
efficiency.

Charge Option  
cc 51-60

0 = no over charging allowed.  
1 = over charging permitted.  
0.1= { re-instates no over  
charging option )

TITLE CARDS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
*TITLE																																																																															
*TITLE																																																																															



## Case Delimiter And Title Cards

Title Cards  
cc. 1-10

Enter '\*TITLE' in columns 1-6 to indicate that the next cards are not data cards but title cards that the user can submit for each case for identification purposes. The user may submit up to five cards containing descriptive information and they must be followed with another '\*TITLE' card. This block of cards may be submitted at any time in the case input data and the user can submit title cards for each parametric case if he so desires.

The title cards are not erased when new ones are read in but instead they are overwritten. This way the user may change only the first card(s) in a set of title cards and retain the other(s) as is. Therefore it is suggested that descriptive material that pertains to several cases be on the last title card(s). In this way the first card(s) can be overwritten in each parametric case with less effort and still provide the full complement of the information.

## Case Delimiter And Title Cards

Keyword Field  
cc. 1-10

Enter '\*END' in columns 1-4 to indicate that the following data is a new base case. However, this card is not needed for the first base case.

Enter '\*PARA' in columns 1-5 to indicate that the following data is to modify the present case. There is no limit to the number of \*PARA cards that may be submitted in a single run.

## Program Structure

### Overall Structure

The Storage Battery Program is divided into four phases:

- o Input
- o Electrochemical calculations
- o Economic calculations
- o Output

The flow of control proceeds in order through the four phases of the program and repeats the cycle until an end of file is sensed on input.

If the program detects an error in any phase it will return immediately to the input phase to process more data.

### Input Phase

The subroutines comprising the input phase are:

INPUT ---- supervisor  
BLOCK DATA  
CHECK  
GETCRD  
PRINT

### Electrochemical Calculation Phase

The subroutines comprising the calculation phase are:

DAILY ----- supervisor  
WEEKLY ----- supervisor  
CYCLE  
MTABLE  
OBJECT

### Economic calculation phase

The subroutines comprising the econ

ECON ----- supervisor  
FNCETF  
FNCVPC  
ZCOOL  
ZFILTER  
ZPUMP  
ZTANK

### Output Phase

The subroutines comprising the output phase are:

OUTPUT ----- supervisor  
OUT1  
OUT2  
OUT3

Subroutine Descriptions

## MAIN

This routine controls the flow through the various phases of the program. If an error is detected in any phase of the program, this routine will direct the program back to the input phase to process more data.

## BLOCK DATA

This routine initializes all the arrays and scalars at the beginning of the program. It also contains the names of the allowable keywords for the input cards and control information for storing the input data.

The array 'CARD' stores the allowable keywords and there are two other arrays associated with it, 'NUM', AND 'ISLOT'. The value of 'NUM(I)' is the number of data fields on the card with the keyword of 'CARD(I)'. The value of 'ISLOT(I)' points to the position in array 'A' right above the place where the information on 'CARD(I)' is to be stored. (see INPUT ).

## CHECK

This routine checks all input data and flags those data items that are zero and are used as divisors in the calculations. If any are found, the program prints out those variables, sets an error code and returns control to MAIN.

This routine is called each time the program completes the input phase. In this way, a data item that was previously zero may be modified such that the program will proceed to the calculation phase.

## CYCLE

This routine performs the daily inventory balances for a weekly cycle. The solution inventories are initialized to zero. A discharge operation decreases the inventory and a charge operation increases it. The inventory will always stay negative unless the overcharging option is chosen. In any case, the last charge cycle will restore the inventory back to the original zero point. The value of the inventory will be the absolute value of the difference between the inventories at the highest and lowest point of the cycle.

## DAILY

The routine follows steps 1 thru 33 in the 'Request For Proposal' which describes the simplified equations for Model 1. The routine determines which power variable is unknown (either by a zero entry, a '-1' entry, or the previous unknown variable) and if it is not the discharge power, it will solve for it directly. Then, the routine proceeds step by step as defined by the RFP to calculate the discharge power and all intermediate variables. The calculated variables are stored in arrays 'C', 'D', and 'E' in the same order in which they are printed by subroutine OUT1.

At several places the routine checks for zero quantities which are used as divisors. If any are detected, the routine branches to an error message and returns to MAIN.

## ECON

This routine handles the bulk of all the economic calculations. It sets up all the necessary data to call the costing routines for the various pieces of equipment in the system. However, it performs the trailer and power conditioning calculations itself.

This routine sets up all the output data except the electrochemical data which is done in subroutine CALC. All data which is to be printed out is stored in an array in the order in which it is to be printed. The costing and sizing calculations are discussed in the appropriate subroutine for each functional section.

The first calculations determine the flow rates in the system, heat duties, and power requirements. Next, the routine does all the cell, stack, and trailer sizing and cost calculations. Next, it sets up the appropriate data for the various functional section equipment, calls the proper routine, and stores the results. The results are stored in scalar variables but they are equivalenced to an output array for convenient I/O.

#### FNCETF

This is a table lookup routine to determine the cooler F<sub>n</sub> factor based on the temperature effectiveness factor.

#### FNCVPC

This is a table lookup routine to determine the power conditioning cost rate in \$/kw as a function of the voltage.



## GETCRD

This routine handles all input processing and determines the keyword on each card. If it is a data card, control is returned immediately to subroutine INPUT. If it is a control card(\*TITLE, \*END, \*PARA), this subroutine will set the appropriate keys and store any necessary information before it returns to INPUT.

## INPUT

This routine controls the input to the program and stores all the input data. All input data is stored in array 'A' in the proper slot corresponding to its keyword(see NUM and ISLOT in BLOCK DATA ).

When the input processing is completed(\*END or \*PARA) this subroutine loads the non-zero entries of array 'A' into a similar array 'B'. Array 'B' is then passed on to the rest of the program.

This routine calls subroutines CHECK, and PRINT. If no errors were detected either by CHECK, GETCRD, or INPUT the routine returns to MAIN. Otherwise, the program stays in the input phase and begins to process additional data.

## MTABLE

This routine prints out the daily tank inventories for a weekly cycle. It also prints out the daily charge and discharge times that were used by the system.

## OBJECT

This routine is an interface routine between the supervisor(WEEKLY) and the calculation routine(CYCLE). It calls the calculation routine with the latest value of current density and returns the cost criterion of the system based on the optimization option chosen.

## OUTPUT

This routine is the output phase supervisor and controls the output of the various tables of data. Although the routine is rather trivial, it provides a handy framework for installing additional user control over the output at a later date. A prime example of this would be some sort of an abort print should an error occur. Then this routine would call only those output reports unaffected by the error.

## OUT1

This routine prints the results of the electrochemical calculations. The FORTRAN variables are printed out also for the convenience of the user. All of the information is calculated in subroutine CALC and stored in arrays 'C', 'D', and 'E'.

## OUT2

This routine prints out the summary of the economic calculations. These data are calculated in subroutine ECON and the appropriate functional section equipment subroutines.

## OUT3

This routine prints out the details of the economic calculations. These data are calculated in subroutine ECON and the appropriate functional section equipment subroutines.

## PRINT

This routine prints the input data as stored by the program. The FORTRAN variables are printed out for the user's convenience along with the proper units.

This printout normally will only appear for base case data. In many cases, the data will be nearly identical for a parameter case and this printout is suppressed. The echo print provided by GETCRD will report the changes made by the user to the base case. However; should the user want to see the input phase print out for a parameter case, he need only supply a '1.0' in the first data field on the \*PARA card that precedes the parameter case data.

## WEEKLY

This is the supervisory routine that handles the weekly cycle calculations. It calls the weekly cycle calculations and if the optimization option is chosen it will manipulate the current density to minimize the optimization criterion.

## ZCOOL

This routine handles the sizing and costing of the air fin coolers in the plant. The coolers are designed to remove the waste heat produced in the trailers both during charge and discharge. Therefore, they are sized to meet the maximum heat duty requirement which can be during either the charge or discharge cycle.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZCOOL, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	duty	mbtu
3	-	
4	fan power	hp
5	-	
6	cooler cost	k\$
7	number of coolers	-

The curve fits used in the cooler calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln(cooler cost)	ln(duty)
ln(fan hp)	ln(duty)

## ZFILTER

This routine handles the sizing and costing of the filters in the plant.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZFILTER, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	number of filters	-
3	size	gpm=275.
4	filter cost	k\$

The curve fit used in the filter calculations is:

<u>y-axis</u>	<u>x-axis</u>
ln(filter cost)	ln(gpm)
sizing- - - none	- - - - -
- - (one size fits all)	- -

## ZPUMP

This routine handles the sizing and costing of the pumps in the plant. The program picks three pumps each one having the capacity of one-half the flow rate. In other words, two pumps are used at full capacity plus a third one to be used as a spare. Should the largest pump size available be inadequate to handle one-half the flow rate, the design basis is changed from three 50% pumps to four 33-1/3% pumps (three operate at full capacity plus a fourth one as a spare). The design basis may change several times in order to accomodate the flow rate.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZPUMP, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>	
1	flow rate	gpm
2	number of pumps	-
3	size	gpm
4	pump cost	k\$
5	motor power	hp

The curve fits used in the pump calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln (pump cost)	sqrt (gpm)
ln (hp)	ln (gpm)

## ZTANK

This routine handles the sizing and costing of the storage tanks in the plant. The program sizes one tank for each reactant plus one common spare. Should the maximum available tank size be inadequate the program will change the design basis to be two equal sized tanks for that reactant. The design basis may change independently for each reactant several times until the tank sizing calculations are complete. Regardless of how many tanks are required to hold a single reactant, there will only be one spare tank of the same capacity as the largest tank.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. This vector is loaded up with the necessary data by subroutine ECON, passed to ZTANK, and the returned data is stored by ECON. The structure of the vector is shown below:

<u>I</u>	<u>ARRAY(I)</u>
1	volume of fluid bbl
2	number of tanks -
3	tank cost k\$
4	mixer power hp

The curve fits used in the tank calculations are:

<u>y-axis</u>	<u>x-axis</u>
ln(tank cost)	ln(bbl)
mixer power	= 0.35*kbb1

# **EXXON** RESEARCH AND ENGINEERING COMPANY

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GOVERNMENT RESEARCH LABORATORIES

## REDOX BULK ENERGY STORAGE SYSTEM STUDY

Contract No. NAS3-19776

Task IIIB

Documentation for Stage 2  
Model Computer Program

By

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Prepared for

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**government  
research**



STAGE 2 MODEL OF REDOX BATTERY ENERGY STORAGE SYSTEM  
PROGRAM DOCUMENTATION PACKAGE

This package documents the Stage 2 Model computer program software and calculation basis. The package contains the following items:

- Discussion of main software features, including logic used in iterative loops, and input data forms required for program execution.
- Appendix 1 - Program structure diagrams giving detailed subroutine operation and interaction.
- Appendix 2 - Outline of computational procedures used in Stage 2 Model of Redox energy storage system.

Model 2 of the Redox Energy Storage System simulates the load-following behavior of a proposed configuration. For small intervals of time, the model calculates the value of the system parameters (flow rate, current density, cell voltage) required to meet the discharge (charge) power of the grid and the resultant change in the reactant concentrations. At the end of a time interval the reactant concentrations are updated and the program moves on to the next time interval. The length of a time interval is controlled by the program based on a user supplied criterion.

The program structure is shown in detail in appendix I on a series of program structure diagrams (PSD's). These are read top down and from left to right. The program is divided into three phases - input, calculations and output. The input phase processes all the input data and is discussed in a following section. The calculation phase consists of two main parts:

- movement along the load profile
- calculation of the instantaneous outlet concentration of the cell

The first part determines how long the cell can operate at the present value of the inlet concentrations of the reactants until one of four criteria is met:

- a change in the load profile
- a tank switch (one tank becomes fully charged or discharged)
- the total flow equals the tank volume
- system performance criterion is not satisfied.

The first two imply an abrupt step change in the system parameters while the second two represent an update to the system parameters as it follows the load profile.

The second part of the calculations is done by integrating the concentration changes and local current density along the cell at the proper value of cell voltage to obtain the desired power. This requires a set of nested convergence loops inside of which is the cell integration calculation.

The output phase summarizes the load profile results at the end of the run or when the program stops due to some incorrecable error.

### Load Profile

The load profile consists of a series of times and power levels. The convention used is that negative power and

current density refer to a discharge operation while positive power and current density refer to a charge operation. Based on the grid power required (available) for a discharge (charge) operation, the program calculates the gross power generated (consumed) by the redox system at an instant in time based on the present value of the reactant concentrations in the tanks. This calculation determines the operating parameters over a certain time period.

The time step taken by the program is determined by what is referred to as a performance criterion. Naturally, as the system operates, the outlet streams of the cells flow to the storage tanks which are assumed to be perfectly mixed. The program assumes a time step, calculates the resulting tank concentration based on the most recent calculated cell outlet conditions and re-calculates the cell voltage, holding the current density fixed. If the percent change in the cell voltage exceeds a user specified criterion, the time step is halved. The performance calculations are repeated until the criterion is met. The initial time step is set to the minimum of the remaining time in the load profile or the time remaining until one tank is fully discharged (charged) or the time to pump one tank volume.

Essentially, the program divides the load profile up into a series of small time steps over which the tank

concentrations are changing slowly. When a tank is fully discharged (charged) the program moves on to the next tank which is fully charged (discharged). If all the tanks are fully charged (discharged) and the load profile is a charge (discharge) operation the program will skip on to the next discharge (charge) operation in the profile. Also, if the time step necessary to meet all criteria is less than one minute, the program will skip the rest of that portion of the load profile and print a message that the system was unable to sustain power.

On a charge operation, if all the available power cannot be used without exceeding a user specified limit on cell voltage, the program will peg the cell voltage at this limit and only use the resulting power. On a discharge operation, if the required power cannot be met, the program will operate at the maximum available power.

### Power Calculations

The program must select a value of cell voltage, calculate the resulting current density and compare the calculated power (adjusted by auxiliary and shunt power and power conditioning efficiencies) to the grid power.

For a discharge operation the initial value of cell

voltage is  $0.8 \cdot E_{REV}$  where  $E_{REV}$  is the reversible cell voltage based on the inlet conditions. The next guess is 0.9 times this value. If the calculated power is converging the program continues to decrease the voltage until the power is reached (or bracketed). If not, the program begins to increase the voltage. Once the grid power has been bracketed the program interpolates to converge on the power. If the program detects that it will never bracket the grid power it uses a golden section search to maximize the power output of the cell.

On a charge operation, the program begins at the maximum cell voltage allowed. If this does not meet the grid power, the program prints out a message to this effect and continues with the performance calculations. If, on the other hand, the maximum power is greater than the grid power then the program simply decreases the voltage level until the grid power is bracketed.

At all times the program checks the value of the cell voltage and insures it stays within the proper limits.

#### Cell Current Density Calculation

Based on the assumed value of the average current density, the program calculates the flow rate for each

reactant. The program then begins to march down the cell calculating the local value of current density and concentration as a function of the distance from the cell inlet. If the flow is laminar then the mass transfer coefficient will also change down the cell and the program not only allows for this but also allows for an entrance effect as well.

At each step down the cell the program considers a "slice" of the cell denoted as  $\Delta x$ . The program calculates the average concentration of each reactant in the slice and then calculates the local current density which depends upon the average concentration. The size of the slice is so chosen that the local current density in a slice differs from that of the previous slice within a certain tolerance. If not, the thickness ( $\Delta x$ ) of the slice is halved, the concentrations, local current density recalculated and compared again with that of the previous slice. This process is repeated until the tolerance is satisfied and only then does the program move on to the next slice.

At the end of each slice the program keeps a running total of the product of the local value of current density and the slice thickness. At the end of the cell calculations, the program divides this sum of products by the cell length to get the average current density. It compares this value with the assumed value and if they

satisfy the tolerance, this loop has converged. If not, the program sets the assumed value of average current density equal to the newly calculated one and repeats the process until it does converge. Also, by the end of the cell calculations, the program has calculated the cell outlet concentrations.

The current densities at the beginning of the cell are changing most drastically and therefore the initial step ( $\Delta x$ ) size is taken as  $L * 10^{-4}$  (L is the cell length). If, the current density drops to a magnitude less than  $10^{-4}$  the cell calculations are terminated for that particular estimate of the current density.

#### Local Current Density Calculations

At each step in the cell current density calculations the program calculates the local current density based upon the local value of the position in the cell, reactant concentrations, and electrode over-potential. There are three unknowns- current density and electrode over potentials, and three equations- complete voltage equation and the Butler-Volmer equations. These are solved using the Newton-Raphson technique and the root mean squared error is the convergence criterion.



As the equations are being solved, certain terms in the Butler-Volmer equations are checked to see if the limiting current has been reached (or exceeded). If so, the current density is fixed at the limiting current and the set of three equations is reduced to two, to solve for the electrode over-potentials.

#### Performance Calculations

When the program has converged on the grid power, the cell voltage, current density and inlet concentration are assumed to remain constant during some time slice. The length of the time slice is determined by several different criteria:

- tank status
- grid status
- performance check

For each criterion, a  $\Delta t$  is calculated and the time slice is chosen to be the minimum  $\Delta t$ . Actually, it is a multi-stage problem. First, the tank status and grid status yield an initial estimate of  $\Delta t$ . Then some of the electrochemical calculations are repeated to yield performance data. If the criteria is met the calculations install  $\Delta t$  as the time slice, if not, it is reduced by

one-half and the performance data are regenerated. This process is repeated until either the performance criterion is met or the time slice falls below one minute.

### Debug Prints

By entering 1.0 in the desired field on the MONITOR1 card the user can follow the program as it converges on the solution to that particular variable. Below is a list of variables printed out for each debug print:

IW1: (1) -

IW1	iteration count in performance check calculations from PROCTX
SUMT	total time thus far at the grid power
TX	total time in grid time slice
R1,R2	reactant concentrations
P1,P2	product concentrations
IBARC	current density

(2)

IW1	from PERFCK
W1	convergence criterion
ECELL	cell voltage at limit of tolerance
ESAVE	cell voltage of system
DT	time step for which system can operate at ESAVE and at the end of which will operate at ECELL

(3)

IW1 . from TNKCAL (upon being called)

R1,R2 reactant concentrations

I1,I1 tank number

(4)

IW1,R1,R2,I1,I2 from TNKCAL (before returning)

TSTATS tank status

TSTAT1,TSTAT2 individual tank status

IW2 :

IW2 iteration counter from PCELL

IH crossover indicator (0=no, 1=yes)

ECELL cell voltage

IBARC current density

PXC calculated power

DPX grid power minus calculated power

IW3 :

IW3 iteration counter in CALPAX

PAUXC auxiliary power

IW4 :

IW4 iteration counter from CALIBR

IBARC calculated average current density

IBARX assumed average current density

QCELL1,QCELL2 reactant flow rates

IW5 :

IW5        iteration counter from CALCDX  
 ILOCLX    local current density at mid point of  
           current     $\Delta x$  slice  
 ILOCL0    local current density at mid point of  
           previous  $\Delta x$  slice  
 ETA1,ETA2 electrode over-potentials  
 X         beginning of  $\Delta x$  slice  
 XB        midpoint of  $\Delta x$  slice  
 K1,K2     diffusion coefficient

IW6 :

IW6        iteration counter from CALCIL  
 ILOCLX    local current density  
 ETA1,ETA2 electrode over-potential

IW7: (1)

IW7        iteration counter from ZSHUNT  
 IL         load    current calculated by shunt program  
 RL         assumed load resistance  
 SPW        shunt power for NS cells.

(2)

Shunt power	}	Upon Convergence
Load current		
Load resistance		
Total shunt power		

### Maximum Iteration Prints

Should any of the convergence loops fail to converge in the desired number of iterations a message will be printed out to this effect with the values of key variables. The variables will be identified with their FORTRAN name and correspond to those in the debug print.

### Convergence Behavior

The tolerances on the various loops should not be set randomly. Many of the converged answers are used to generate functions which must be used to converge still more loops, etc. For example a loose tolerance on IBARC (IW4) or too few iterations might allow the program to predict an erroneously high value of current density resulting in a high power density, when a few more iterations would have converged properly on a lower value. This may mislead the program in its search for the maximum power on a weak discharge operation or even send the power calculations in the wrong direction. Below are some guidelines:

IW1 :

too loose a tolerance will tend to overpredict system performance. System will maintain conditions over a longer time slice than in actuality. System will discharge in big steps.

IW2 :

tolerance can be specified at user's desire. Too loose a tolerance and the program will only approximate power curve; too tight causes excessive iterations.

IW3 :

no loop at all

IW4 :

too loose a tolerance may cause erroneous value of average current density that could effect entire calculations; too tight causes more iterations.

IW5 :

too loose a tolerance will tend to overpredict current density; too tight may cause program to hang up marching down the cell.

IW6 :

too loose a tolerance will yield erroneous and erratic results in all subsequent calculations; too tight causes excessive iterations.

IW7 :

too loose a tolerance yields a poor estimate of shunt losses; too tight appears to be no problem.

Description of Subroutines

## CALCDX -

This routine marches down the cell calculating the value of local current density and electrode over potentials. It initializes the local current density at  $x = 0$  to 3.5 times the average current density. The step size is initialized to  $L * 10^{-4}$  and the concentrations are evaluated at the average value of  $x$  in the slice. The step size is small because the current density changes rapidly at the beginning of the cell. The step size is doubled for each subsequent  $\Delta x$  calculation. If the value of the local current density fails to fall within the tolerance (TOL5) of the previous value of the current density the step size is cut in half. Typically, the step size will be cut in half a few times at the beginning of the cell and will double thereafter except for an occasional halving. If the current density falls below  $1 \times 10^{-4}$  in magnitude the routine assumes the rest of the cell

does not contribute to the average current density and it skips to the end of the cell.

#### CALCFZ -

This is the calculation phase supervisor. It performs all tank initialization and sizing calculations and then turns control over to TGRCAL.

#### CALCIL -

This routine supervises the solution of the local current density and electrode over potentials. It initializes the current density and sets the electrode overpotentials equal to plus or minus the current density. It calls CALDIL to generate the changes in the three solution variables. For stability sake the changes allowed are pegged to a maximum size based on the previous step. The first time (at  $x=0$ ) this technique may take anywhere from eight to fifteen iterations but thereafter usually only takes four to six to converge. The criterion is the root mean square error. This is a fairly stringent



criterion but this solution is critical for the model.

#### CALCK

This routine calculates the value of the reactant diffusion coefficient based on flow rate and cell position (laminar flow).

#### CALDIL -

This routine contains the derivatives necessary for the Newton-Raphson solution of the local current density and electrode overpotentials. It also checks for the limiting current and, if it occurs, pegs the current density to this value and reduces the three equations to two and solves them. The electrode overpotentials should always be of opposite sign. The sign of the one corresponding to reactant 1 is the same as the sign of the current density. There are continuing checks in this routine. If they are ever violated the program stops and prints out the results obtained thus far.

## CALIBR -

This routine calculates the average current density in the cell. The initial estimate is based on the user supplied value. The flow rate of each reactant is based on the average current density. The routine calls CALCDX to calculate the local current density down the cell and the average current density over the entire cell. If the calculated current density is within the tolerance (TOL4) of the estimated current density the program considers this calculation converged. If not, the program makes a ten percent change in the estimated current density in the direction of the calculated current density. Thereafter, the program takes the latest two sets of estimated and calculated current density and interpolates to get the next value of estimated current density. However, the maximum change permitted is 50 % of the latest value. This approach was taken to put stability in the calculations since oscillations can occur due to the flow rate dependence on the current density.

## CALPAX -

This routine supervises the average current density, auxiliary power and shunt calculations. It also calculates the gross redox system power which is used by PECELL to calculate the net redox system power.

## CON SIS -

This routine performs a series of consistency checks on the input data regarding the cell measurements. If any are not satisfied the program prints a message and terminates.

## COST

This routine sizes and costs all equipment for the system. It calls upon the same routines used in model 1.5.

## ECON -

This routine keeps track of the minimum and maximum flow rates and maximum cooler duty. This information is needed at the end of the time grid calculations to size and cost out the equipment.

FNCETF -

This is a table lookup routine to determine the cooler Ft factor based on the temperature effectiveness factor.

FPCVPC -

This is a table lookup routine to determine the power conditioning cost rate in \$/Kw as a function at the voltage.

INFAZE -

This routine reads and processes all the input data. The data cards may be read in any order. Up to 200 grid cards are allowed and they must be enclosed between two '\*GRID' cards.

MAIN -

Supervisor of program. It controls the calculation flow from one phase to another. IER is an error code which is initialized to zero and passed to all supervisory routines. If IER  $\neq$  0 at any time the program will print the output results obtained thus far.

## OUTFZ -

This is the output supervisor routine. It prints out the time grid results and calls upon the rest of the output routines.

## PECELL -

This routine determines the value of cell voltage required to achieve the grid power. It starts at 0.8 times the reversible voltage for a discharge operation or at the maximum allowable cell voltage for a charge operation. The second guess of the cell voltage is 0.9 times the first. Each time, it calculates the average current density based on the assumed cell voltage, and the resulting power. On charge it continues to reduce the cell voltage until the grid power is bracketed. For discharge it does the same but also can detect if it is going in the wrong direction or if it appears to have passed the right value. If it can't bracket the discharge power it uses a golden section search to get the maximum power out of the cell. At all times the routine checks for valid upper and lower limits on the cell

voltage. It also calls upon the auxiliary power calculations.

PECFCK -

This routine decides upon the  $\Delta t$  for which the system can operate within certain limits. If the cell outlet concentrations are above the minimum allowed, the maximum value of  $\Delta t$  is set to the tank volume divided by the flow rate (one tank turnover). If the cell outlet concentrations are below the minimum allowed, the maximum value of  $\Delta t$  is set to that which would produce an average tank concentration equal to the minimum allowed. The minimum value of the maximum  $\Delta t$  is chosen for the performance calculations. The routine calls PRFCAL and either accepts the  $\Delta t$  as is or cuts it in half, and repeats the performance calculations until satisfied or until  $\Delta t$  falls to less than one minute. If the performance check reduces  $\Delta t$  to less than one minute the program prints out a "failure to sustain power" message and skips to the next grid time.

## PRFCAL -

This routine actually does the performance check calculations. After the tank concentrations have been updated, this routine picks a cell voltage that exactly meets the performance tolerance (TOL1). This routine calls CALIBR, and if the magnitude of the calculated current density is greater than that just calculated, that is equivalent to a cell voltage within the voltage tolerance at the original current density. If not, the time step is cut in half and tried again.

## PROCTX -

This routine processes a set of time and power data from the grid data. It checks the tank status and proceeds to the power calculations if the tank status and grid power are consistent. If not, it flushes that particular grid time and moves on to the next.

The power calculations may divide the grid time up into a number of time slices and

this routine keeps track of when the sum of the slices equals the grid time. This time-slicing will happen more often for small tanks where the concentration is changing fast and when the grid power cannot be met. The control over the time-slicing is in subroutine PERFCK which does the performance check calculations.

If the grid power is a discharge operation and all the tanks of at least one reactant have become fully discharged, or if it is a charge operation and all such tanks have become fully charged, the remaining time of the operation will be flushed and the program moves on to the next one (returns to TGRCAL).

#### SHUNT -

This routine is essentially the program written by P. Prokopius of NASA (216-433-4000, ext. 6639) to calculate the shuntage power loss in a series of cells.



## STOREO -

This routine sets up the output of the time grid data. It is called when the calculations are complete or when a fatal error causes termination.

## TGRCAL -

This routine is the supervisor of the time grid calculations. It initializes the tank concentrations, tank limits and tank status. It controls the calls to PROCTX based on the tank status.

## TNKCAL -

This routine checks the concentration levels of the tanks. If the concentration is below the minimum allowed, the tank counter is increased by one and the concentration set equal to the maximum. If the tank concentration is greater than the maximum allowed, the tank counter is reduced by one and the concentration is set equal to the minimum. This routine also sets counter to indicate a fully charged or discharged state.

## TRLCAL -

This routine calculates the number of stacks per trailer. The routine first calculates the size of a substack of cells and tries to arrange as many stacks as possible into a trailer by considering different packing orientations.

## UPCONC -

This routine updates the concentrations of the two reactants based on the value of the local current density as the calculations proceed down the cell.

## ZCOOL -

This routine handles the sizing and costing of the air fin coolers in the plant. The coolers are designed to remove the waste heat produced in the trailers both during charge and discharge. Therefore, they are sized to meet the maximum heat duty requirement which can be during either the charge or discharge cycle.

All information passed to and from this

routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20.

The structure of the vector is shown below:

ARRAY(I)		
<hr/>		
1	FLOW RATE	GPM
2	DUTY	MBTU
3	-	
4	FAN POWER	HP
5	-	
6	COOLER COST	K\$
7	NUMBER OF COOLERS	-

The curve fits used in the cooler calculations are:

Y-AXIS	X-AXIS
<hr/>	
LN(COOLER COST)	LN(DUTY)
LN(FAN HP)	LN(DUTY)

ZFILTER -

This routine handles the sizing and costing of the filters in the plant.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. The structure of the vector is shown below:

I	ARRAY(I)
1	FLOW RATE GPM
2	NUMBER OF FILTERS -
3	SIZE GPM=275.
4	FILTER COST K\$

The curve fit used in the filter calculations is:

Y-AXIS	X-AXIS
LN (FILTER COST)	LN (GPM)
SIZING- - - NONE - - - - -	
- - (ONE SIZE FITS ALL) - -	

ZPUMP -

This routine handles the sizing and costing of the pumps in the plant. The program picks three pumps each one having the capacity of

one-half the flow rate. In other words, two pumps are used at full capacity plus a third one to be used as a spare. Should the largest pump size available be inadequate to handle one-half the flow rate, the design basis is changed from three 50 % pumps to four 33-1/3 % pumps (three operate at full capacity plus a fourth one as a spare). The design basis may change several times in order to accomodate the flow rate.

All information passed to and from this routine is done by using a dummy vector called 'ARRAY' which is dimensioned for 20. The structure of the vector is shown below:

I	ARRAY(I)	
1	FLOW RATE	GPM
2	NUMBER OF PUMPS	-
3	SIZE	GPM
4	PUMP COST	K \$
5	MOTOR POWER	HP

The curve fits used in the pump calculations are:

Y-AXIS	X-AXIS
LN (PUMP COST)	SQRT (GPM)
LN (HP)	LN (GPM)

ZSHUNT -

This is the supervisory routine for the shuntage loss calculations. The routine SHUNT requires the load resistance as one of the inputs and calculates load current as one of the outputs. However, the program already knows the load current but not the load resistance. Therefore, it assumes a value of load resistance and iterates until it matches the load current.

The shunt calculations are unstable outside a narrow range of load resistance. Beginning with a load resistance at zero the resulting load current is slightly negative. As the load resistance increases, the current changes little, until near the critical value of load resistance, the current decreases hyperbolically to negative

infinity and then suddenly reverses and goes to positive infinity. As the resistance increases still further the current decreases hyperbolically and approaches a small positive value. The convergence technique in ZSHUNT captures this behavior and in conjunction with a good initial guess, it usually converges rapidly.

#### ZTANK -

This routine handles the sizing and costing of the storage tanks in the plant. The program sizes one tank for each reactant plus one common spare. Should the maximum available tank size be inadequate the program will change the design basis to be two equal sized tanks for that reactant. The design basis may change independently for each reactant several times until the tank sizing calculations are complete. Regardless of how many tanks are required to hold a single reactant, there will only be one spare tank of the same capacity as the largest tank.

All information passed to and from this routine is done by using a dummy vector

called 'ARRAY' which is dimensioned for 20.

The structure of the vector is shown below:

I	ARRAY(I)
<hr/>	
1	VOLUME OF FLUID BBL
2	NUMBER OF TANKS -
3	TANK COST K\$
4	MIXER POWER HP

The curve fits used in the tank calculations are:

Y- AXIS	X- AXIS
<hr/>	
LN ( TANK COST )	LN(BBL)
MIXER POWER	= 0.35*K*BBL



										Maximum Iterations for loops 1→7																																																																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ITERATION1																																																																															
										IW1MAX										IW2MAX										IW3MAX										IW4MAX										IW5MAX										IW6MAX										IW7MAX									

										Enter a 1.0 to get debug print for the loop																																																																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
MONITOR1																																																																															
										IDBUG1										IDBUG2										IDBUG3										IDBUG4										IDBUG5										IDBUG6										IDBUG7									

										Convergence tolerance for loops 1→7																																																																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
TOLERANCE1																																																																															
										TOL1										TOL2										TOL3										TOL4										TOL5										TOL6										TOL7									





										Initial Reactant Concentration (g moles/l.)	Reactant Utilization Factor										Delivered Cost of reactant Solutions \$/kg										
1	2	3	4	5	6	7	8	9	10		Maximum		Minimum																		
REAC1	C	0	N	C																											
										C1											CR1										

										Initial Reactant Concentration (g moles/l.)	Reactant Utilization Factor										Delivered Cost of reactant Solutions \$/kg										
1	2	3	4	5	6	7	8	9	10		Maximum		Minimum																		
REAC2	C	0	N	C																											
										C2											CR2										

										Supporting Electrolyte Concentration (g moles/l.)										Molecular Weight of Supporting Electrolyte										Delivered Cost of supporting Electrolyte \$/kg																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
ELEC0NC																																																																															
										C1S										C2S										MWSE										CSSE																																							











										Manifold Width										Manifold Length										Number of Manifolds																																																	
										(cm)										(cm)										(cm)										(cm)																																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
MANIFOLD																																																																															
										XMNW1										XMNW2										XMNL1										XMNL2										NM1										NM2																			

										Port Width										Port Height										Number of Ports																																																	
										(cm)										(cm)										(cm)										(cm)																																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
PORT																																																																															
										PW1										PW2										PH1										PH2										NP1										NP2																			

										End Plate plastic cost \$/kg		Substack end plate plastic Cost \$/kg		Substack end plate conductor & tab cost \$/kg		Cell Frame Plastic Cost \$/kg		Current Collector Plate Cost \$/kg		Electrode Deposit Cost																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
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										Membrane Resistivity (ohm cm)	Membrane Thickness (cm)	Membrane Cost (\$/kg)	Support Screen Cost									
1	2	3	4	5	6	7	8	9	10				(A) \$/m <sup>2</sup>	(B) \$/m <sup>2</sup>								
MEMBRANE																						
										RHØ	DELTA	CM	CSSA	CSSB								

										Redox Converter Operating Temperature (°C)	Ambient Air Temperature (°C)												
1	2	3	4	5	6	7	8	9	10														
TEMP																							
										TCELL	TAIR												







										Initial guess of current density (amps/cm2)										Maximum cell Voltage (volts)										Pump power factor (--)																																																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
INITIALIZE										IBAR0										EMAX										FP																																																	



1-1

APPENDIX 1

PROGRAM STRUCTURE DIAGRAMS



# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE	OF
					MTH	DAY	YR			

11 01 76

1

1

1

1 ZERO OUT COMMON  
 ARRAYS - A, TGRID,  
 PGRID, ISI, IS2, IS3, IS4,  
 IFR0M1, IFR0M2, IT01, IT02,  
 POUT, PDEMAND, ISTAT1,  
 ISTAT2, RUC0N0, RUC0N1

A

B

C

D

E

F

G

1

2

3

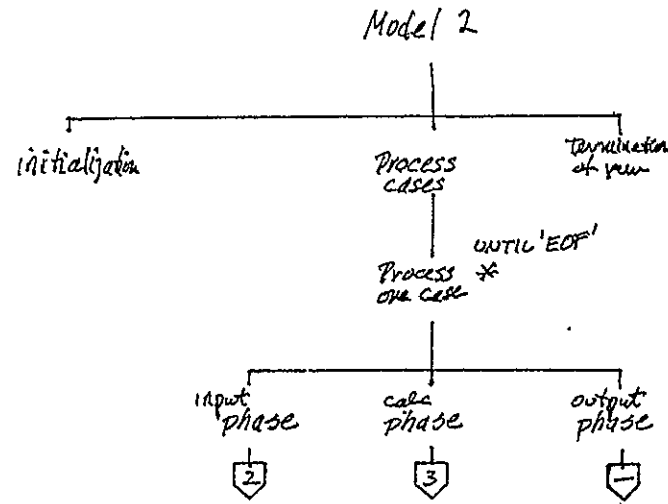
4

5

6

7

8



1-2

1

2

3

4

5

6

7

8

6-6

EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

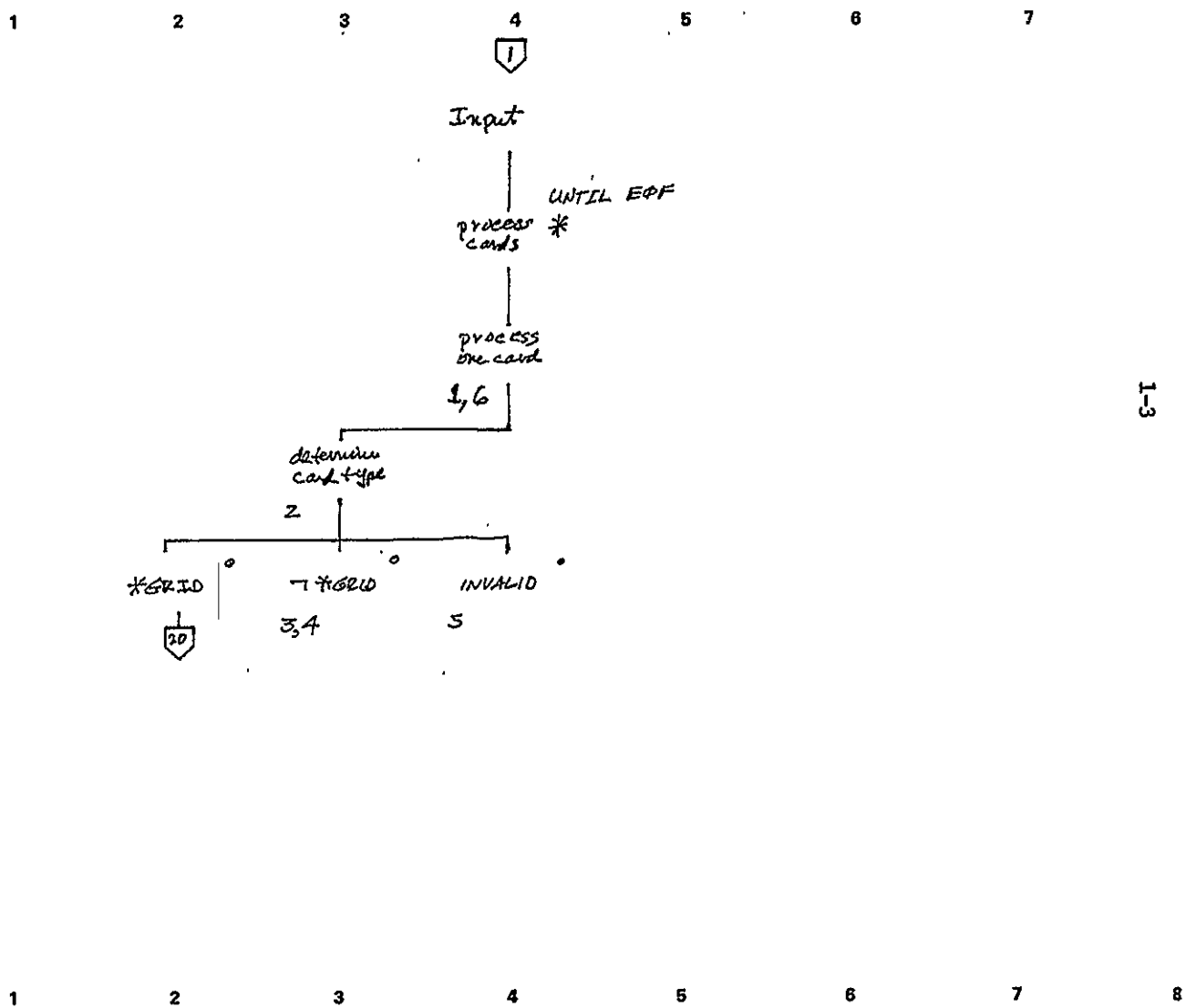
PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTN	DAY	YR		

1	1	0	9	7	6
---	---	---	---	---	---

2

- A
- B
- C
- D
- E
- F
- G

1. READ NAME, DUMMY  
 2. FIND I such that NAME  
 = CARD(I)  
 3. IX = 7\*(I-1)  
 4. A(IX+J) = DUMMY(J), J=67  
 5. print card+message+STOP  
 6. print card



1-3

# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED	REFERENCE NO:	PAGE
					MTH DAY YR	3	0
					1 1 0 19 7 16		

1. Calc  $\eta_{cycle}$

2. Find  $|P_0|_{max}$  in  $|P_{cycle}|$   
 $= P_{max}$

3. Calculate  $max(\sum P_0, t_{ci})$   
 for a "part" of charge cycle  
 times (continuous)

4. Do R-1 calcs:

a. Calc.  $E_{cell}$  for 3 conc.  
 on charge + discharge

b. for charge find  $P_{cell min}$

c. for discharge find  $P_{cell max}$

d. for final #s in b + c.  
 pick  $P_{cell min}$  +  
 corresponding  $E_{cell min}$

e. Calc.  $A, N_T$

5. Set  $N_T$ ,  $E_{cell min}$  = to user  
 values.

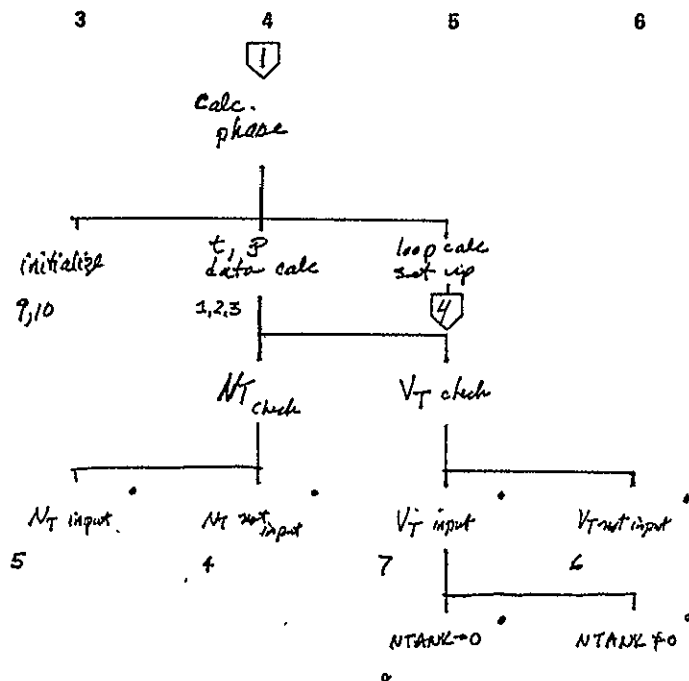
6. Do R-2 calcs to get  
 $V_1$  and  $V_2 \Rightarrow M_1, M_2$

7. Set  $M_1, M_2$  = to user values

8. call ZTANK for sizing

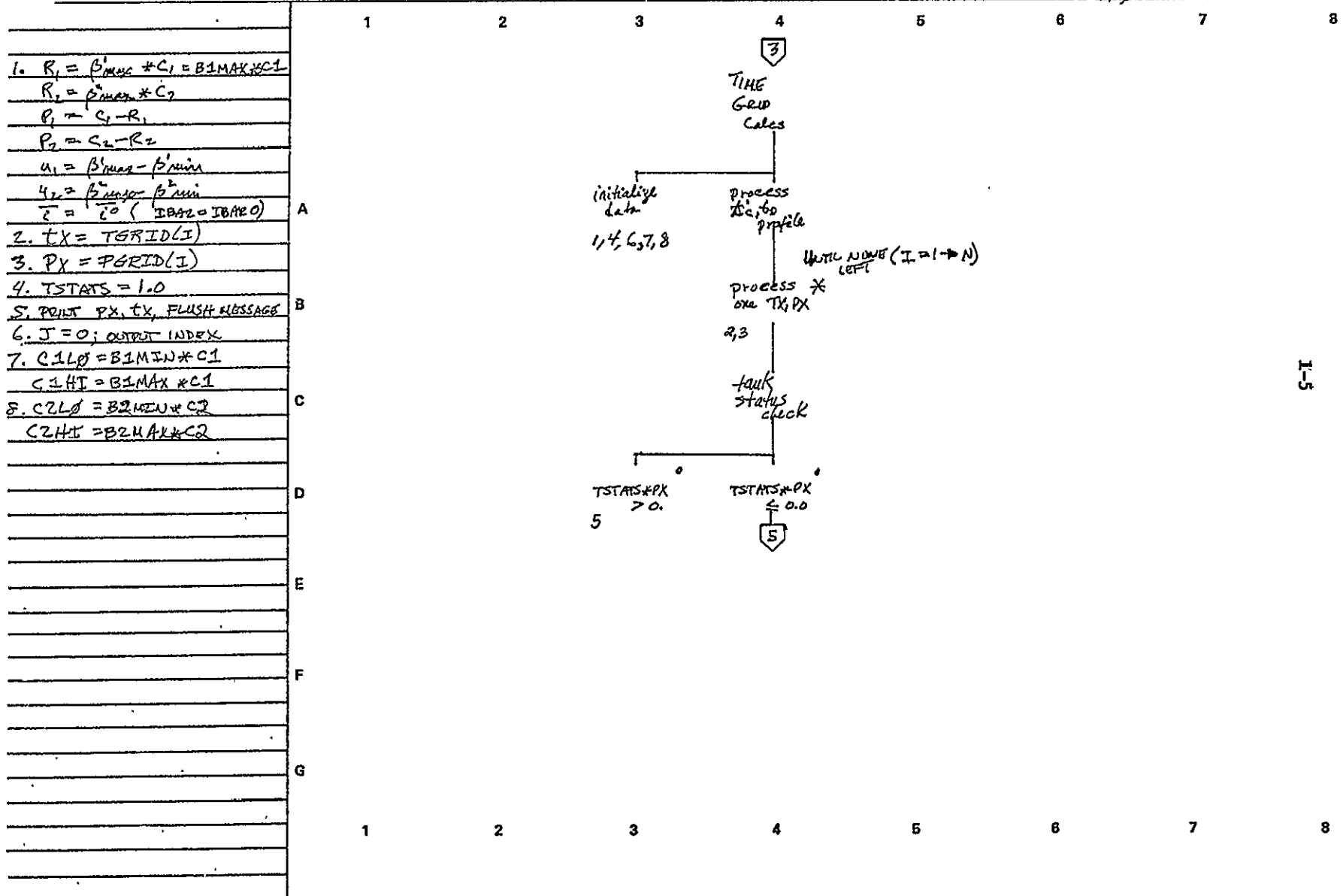
9.  $FARADY = 96,520$ .

10.  $SC1 = VISC1 / (RHO1 * D1)$   
 $SC2 = VISC2 / (RHO2 * D2)$



# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					1	1	74	4	



EXXON MCS — PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE	OF
					MTH	DAY	YR			

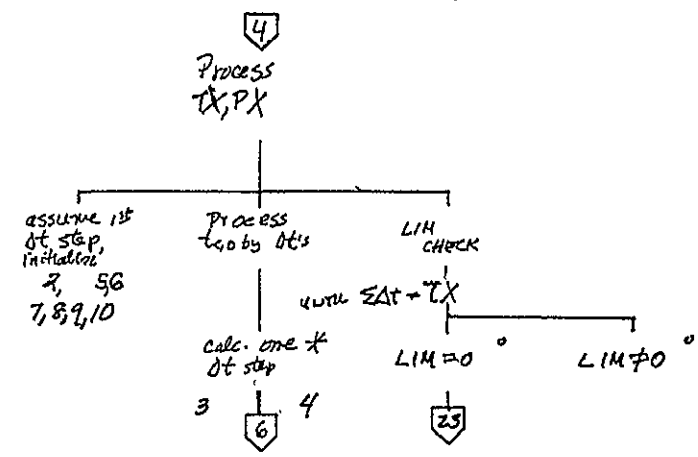
11 76

5

1 OF

1 2 3 4 5 6 7 8

A  
2.  $SOUT = 0.0$   
3  $R1X = R1$   
 $R2X = R2$   
 $P1X = P1$   
 $P2X = P2$   
B  
4  $ISAX = ISARX$   
5. calc  $EREV$  via R-4 (1) (pseudos)\*  
6.  $ECOLL = EREV \times 0.7$   
D  
7  $IT1 = IS1(I)$   
8  $IT2 = IS2(I)$   
9  $IT3 = IS3(I)$   
10  $IT4 = IS4(I)$   
E



1-6

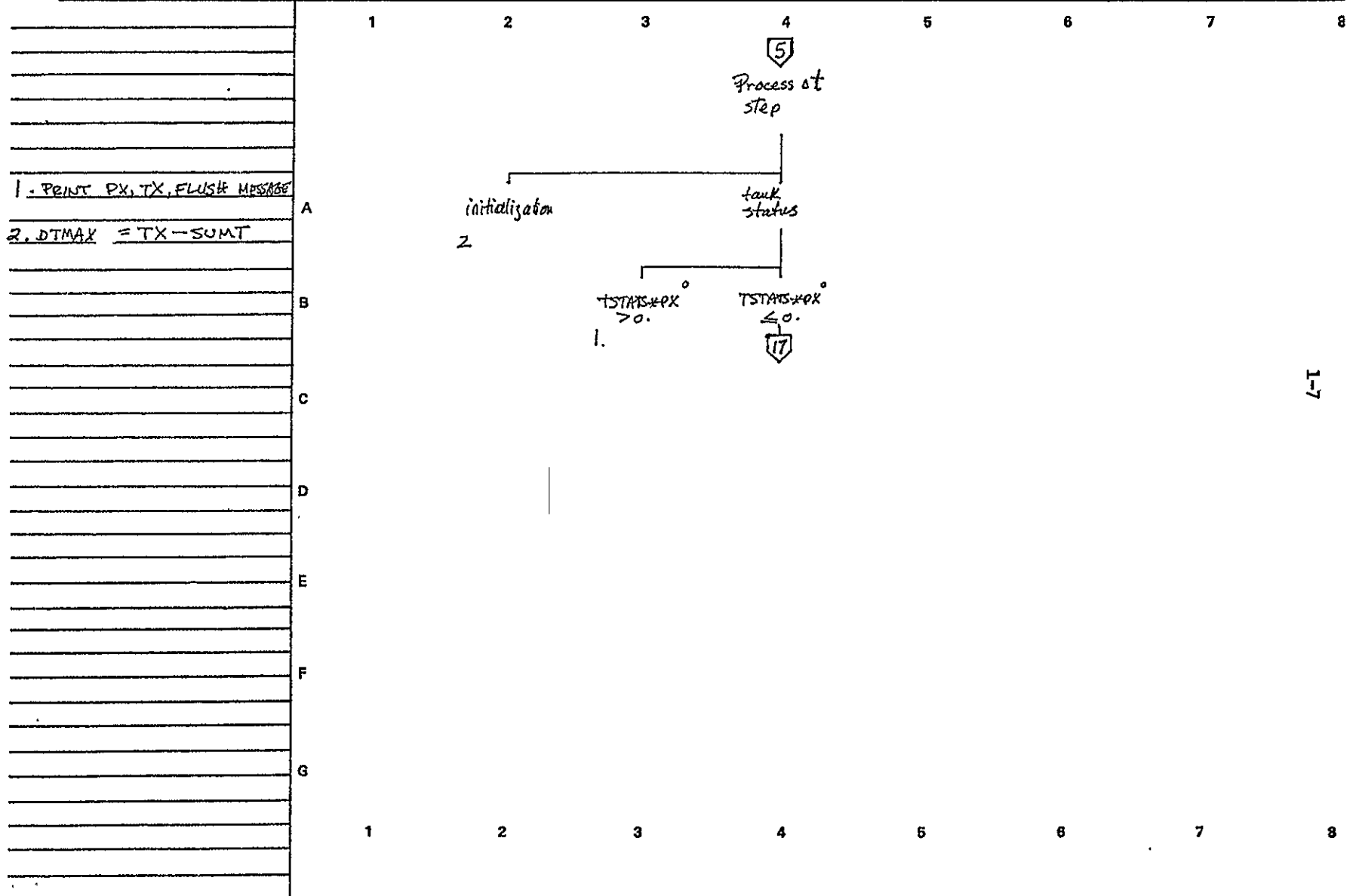
$$EREV = (E10 - E20) + 3.3 * (TCELL + 273) / PARADY * ALDG( (R1/P1) * (1/Z1) * (R2/P2) )$$

\*See Page 1-15 for definition.

1 2 3 4 5 6 7 8

# EXXON MCS -- PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	09	76	6	



# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	10	97	7	0

$$1. PAUX = 0.05 * PX$$

$$2. IW2 = IW2 + 1$$

$$3. IW3 = 0$$

$$4. ICONF3 = 0$$

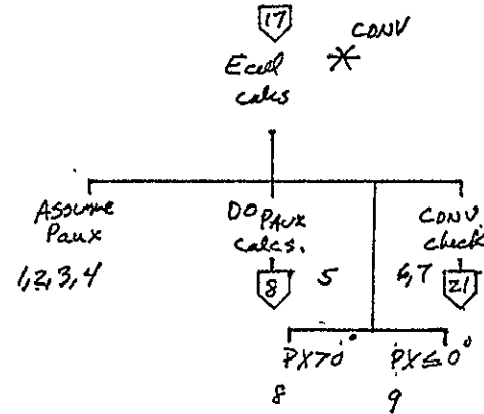
$$5. PXNC = PXC - PSHUNT$$

$$6. CRIT = (PXNC / PXN)$$

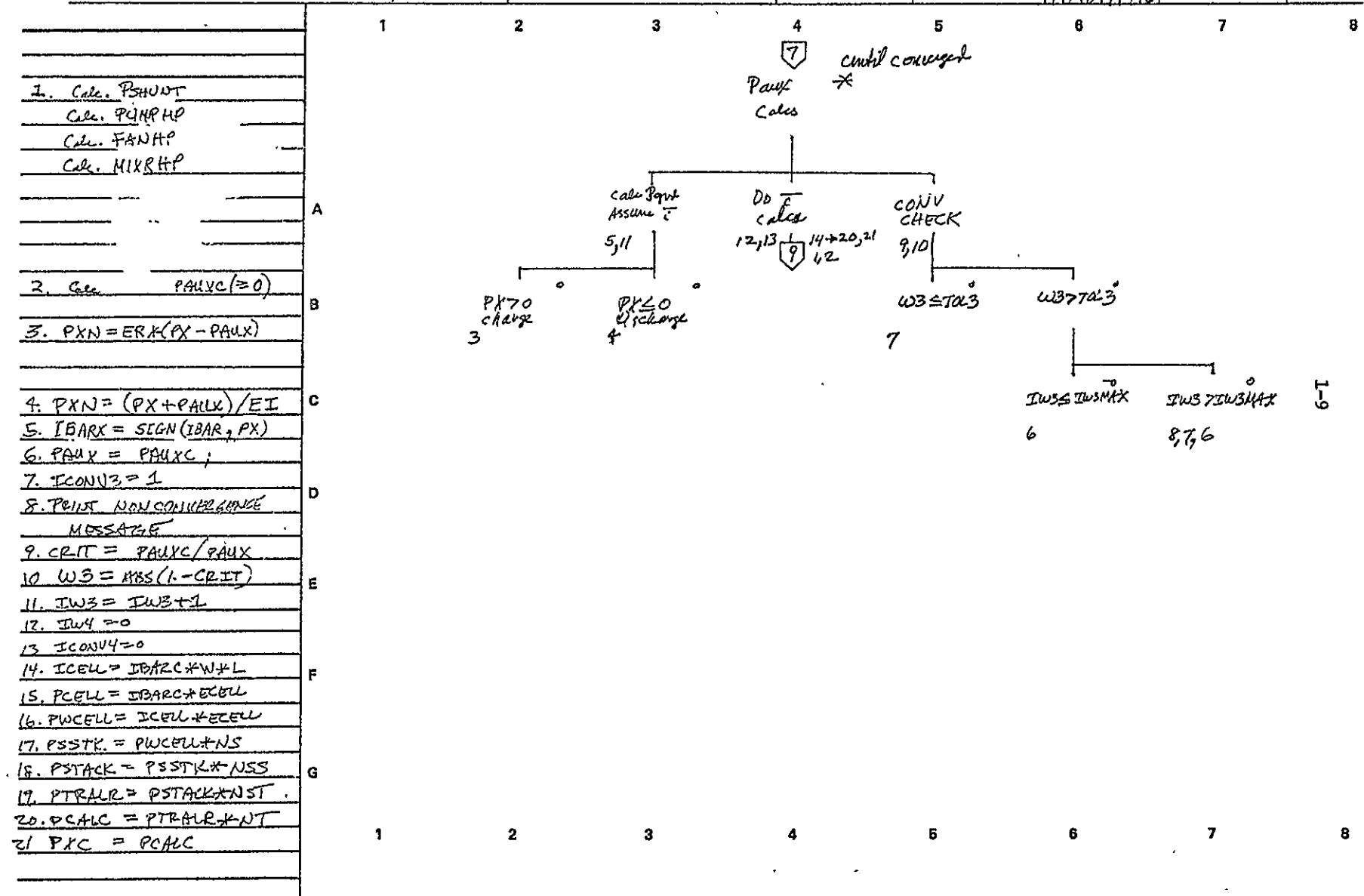
$$7. W2 = ABS(1 - CRIT)$$

$$8. PREDOX = PXC / ER + PAUX$$

$$9. PREDOX = PXC * EI - PAUX$$



PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE	O
					MTH	DAY	YR			
					11	01	76	8		





EXXON MCS — PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE	OF
					MTH	DAY	YR			

1.  $Q_{CELL} = f(\tau)$   
 $NRE = f(\nu_{cell}); dh = f(w, \tau)$   
 2.  $X = 0.0$   
 3.  $DX = \frac{1}{10} (1.0 \times 10^{-2} * L, .73 dh)$

5.  $ILCLX = IBARX * 3.5$

6.  $SIX = 0.0$

7.  $SDX = 0.0$

8.  $ETA1 = IBARX * ILCLX$

9.  $ETA2 = -ETA1$

10.  $DX0 = DX$

11.  $ILCLO = ILCLX$

12.  $R1C = R1X; P1C = P1X$

13.  $R2C = R2X; P2C = P2X$

14.  $IBARX = IBARC$

15.  $W4 = IW4 + 1$

16.  $CRIT = IBARC / IBARX$

17.  $W4 = ABS(1 - CRIT)$

18.  $ICONV4 = 1$

19. PRINT NON-CONVERGENCE  
 MESSAGE

A

B

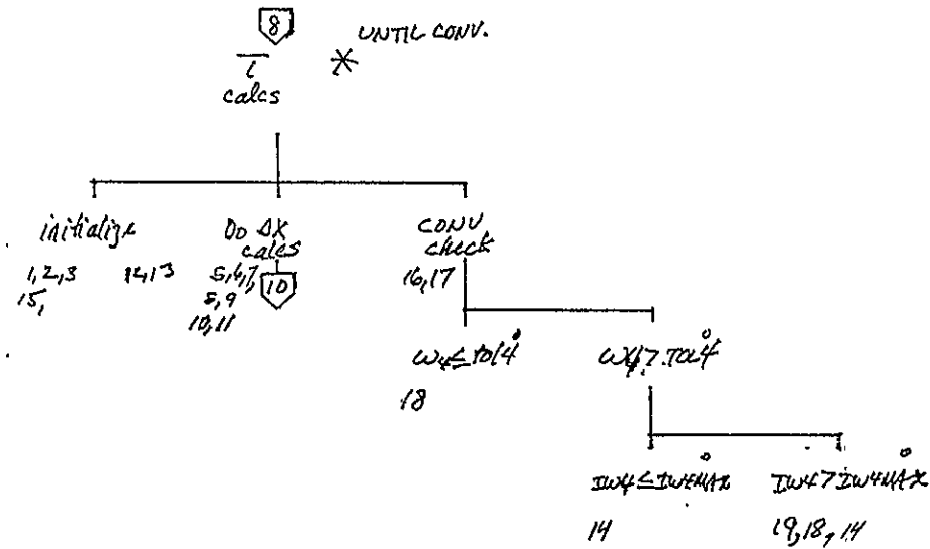
C

D

E

F

G



1-10

$$Q_{CELL1} = \frac{F1 * W * L * IBARX * 10^3}{E1 * PARADY * U1 * C1}$$

$$Q_{CELL2} = \frac{F2 * W * L * IBARX * 10^3}{E2 * PARADY * U2 * C2}$$

$$QV1 = Q_{CELL1} / (\tau_{AU1} * W)$$

$$QV2 = Q_{CELL2} / (\tau_{AU2} * W)$$

$$dh1 = \frac{2(\tau_{AU1})W}{(\tau_{AU1} * W)}$$

$$dh2 = \frac{2(\tau_{AU2})W}{(\tau_{AU2} * W)}$$

$$RE1 = \frac{dh1 * QV1 * RH01}{2 * 2}$$

$$RE2 = \frac{dh2 * QV2 * RH02}{2 * 2}$$

1

2

3

4

5

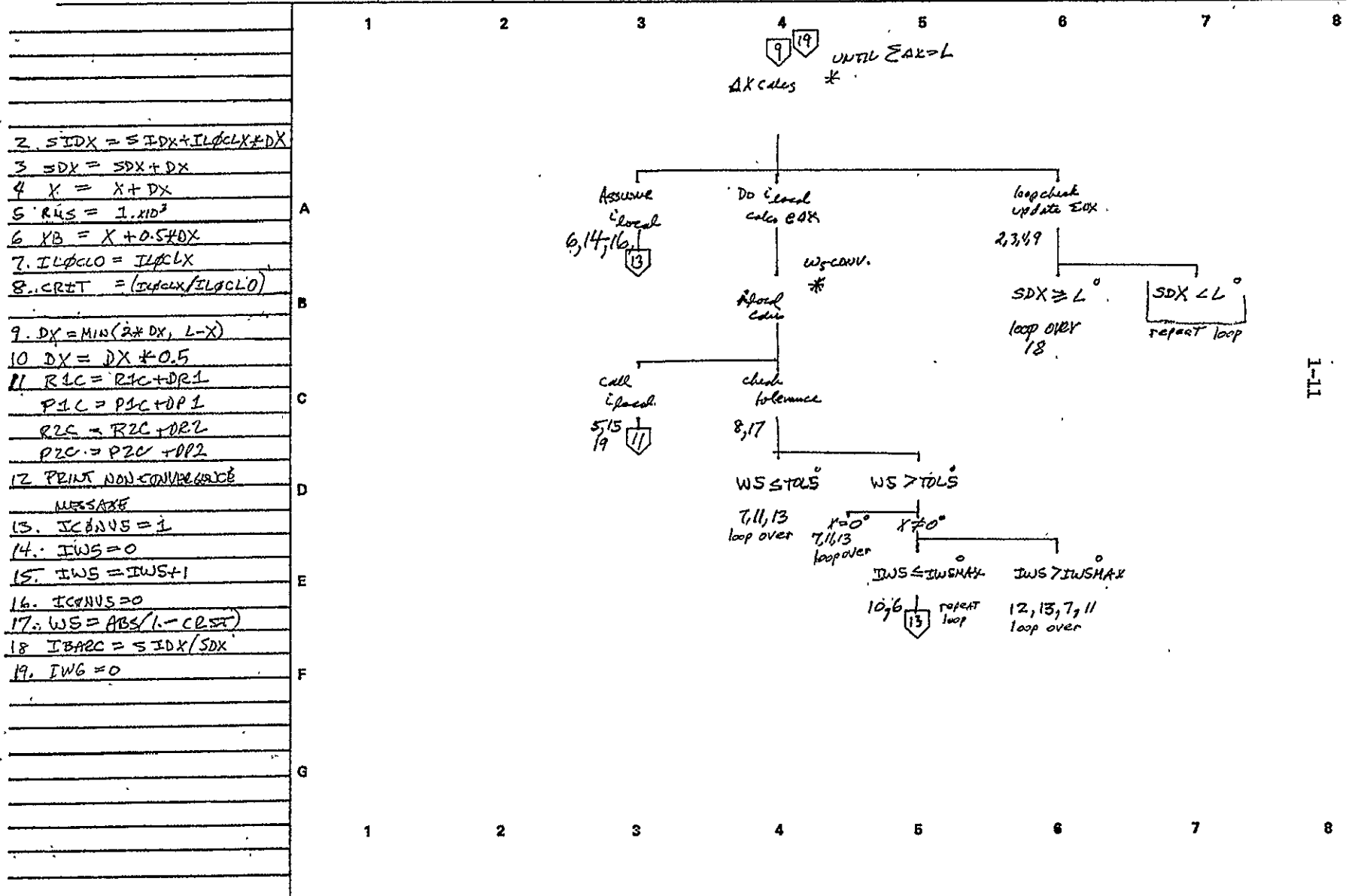
6

7

8

# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	21	96	10	0



# EXXON MCS — PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	19	71	11	1

$$1. W6 = \text{SQRT}((\Delta i^2 + \Delta \eta_1^2 + \Delta \eta_2^2)/3)$$

$$2. ILOPNV6 = 1$$

$$3. \Delta i = \Delta i \times 0.5$$

$$\Delta \eta_1 = \Delta \eta_1 \times 0.5$$

$$\Delta \eta_2 = \Delta \eta_2 \times 0.5$$

$$4. r_1 = \text{new } \Delta i / \text{old } \Delta i$$

$$r_2 = \text{new } \Delta \eta_1 / \text{old } \Delta \eta_1$$

$$r_3 = \text{new } \Delta \eta_2 / \text{old } \Delta \eta_2$$

$$5. r_{\text{max}} = \text{MAX}(r_1, r_2, r_3)$$

$$6. r_{\text{max}} = 1/r_{\text{max}}$$

$$7. r_{\text{max}} = 1$$

$$8. \text{new } \Delta i = \text{new } \Delta i \times r_{\text{max}}$$

$$\text{new } \Delta \eta_1 = \text{new } \Delta \eta_1 \times r_{\text{max}}$$

$$\text{new } \Delta \eta_2 = \text{new } \Delta \eta_2 \times r_{\text{max}}$$

9. Print non-convergence message

$$10. IW6 = IW6 + 1$$

$$11. \text{old } \Delta i = \text{new } \Delta i$$

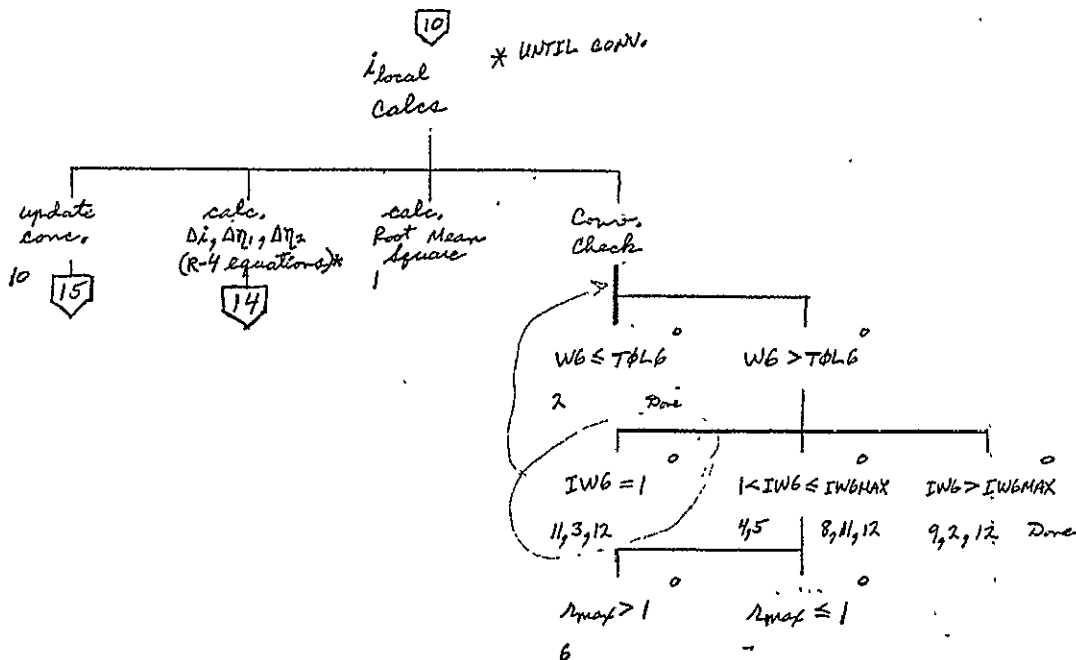
$$\text{old } \Delta \eta_1 = \text{new } \Delta \eta_1$$

$$\text{old } \Delta \eta_2 = \text{new } \Delta \eta_2$$

$$12. ILOCLX = ILOCLX + \text{new } \Delta i$$

$$\text{ETA1} = \text{ETA1} + \text{new } \Delta \eta_1$$

$$\text{ETA2} = \text{ETA2} + \text{new } \Delta \eta_2$$



\*See Page 1-15 for definition.

1-12

# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE	O.
					MTH	DAY	YR			
					11	10	97	12		

1  $E_{cell} = E_{cell} * I_{BARX} / I_{BARC}$

2  $CRIT = I_{BARC} / I_{BARX}$

3  $W_4 = ABS(1 - CRIT)$

4  $I_{WH} = I_{WH1}$

5  $TECONV = 1$

6 Print NON-CONVERGENCE message

7  $E_{CELL} = E_{CELL} * I_{BARC} / I_{BARX}$

A

B

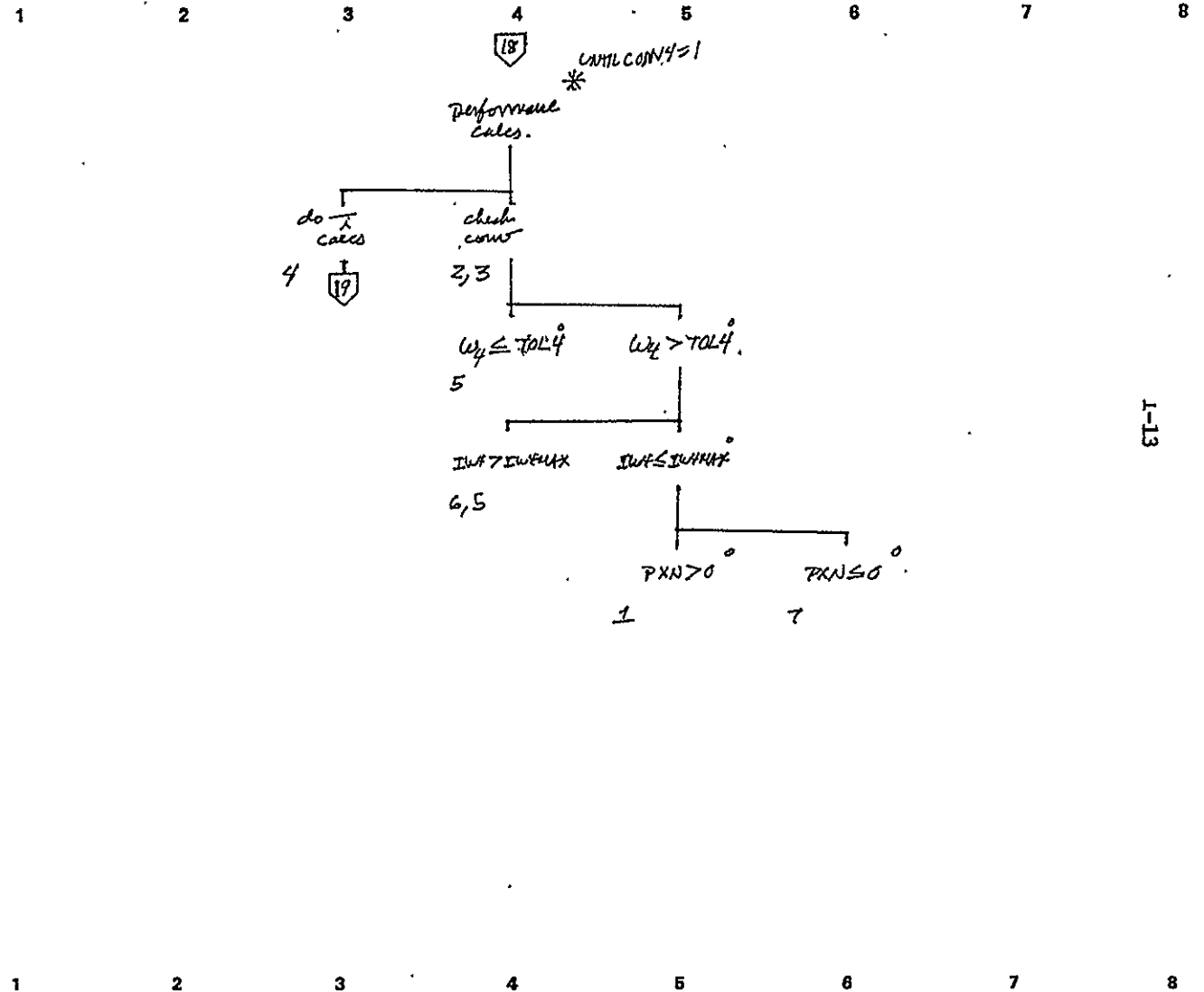
C

D

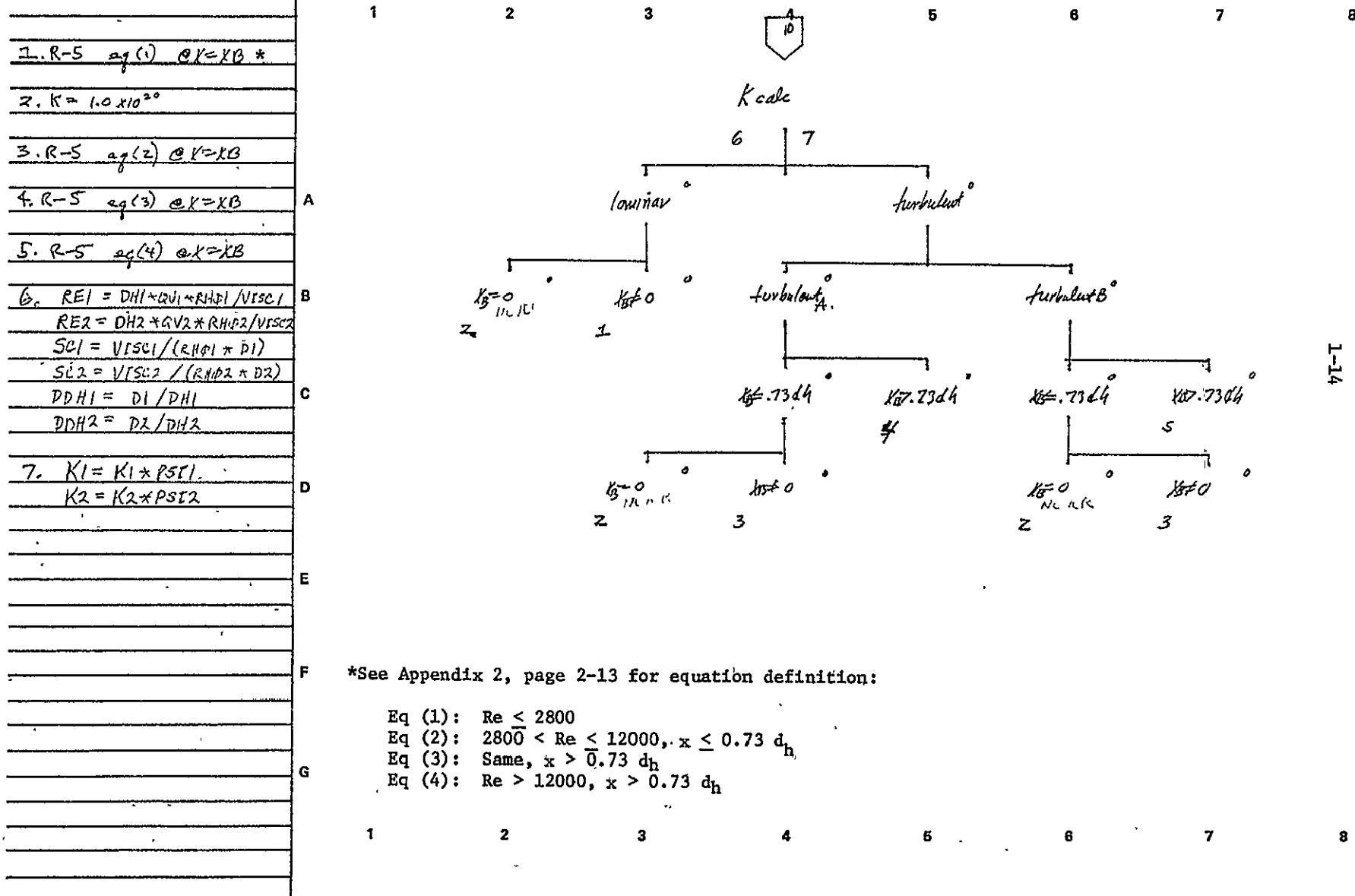
E

F

G

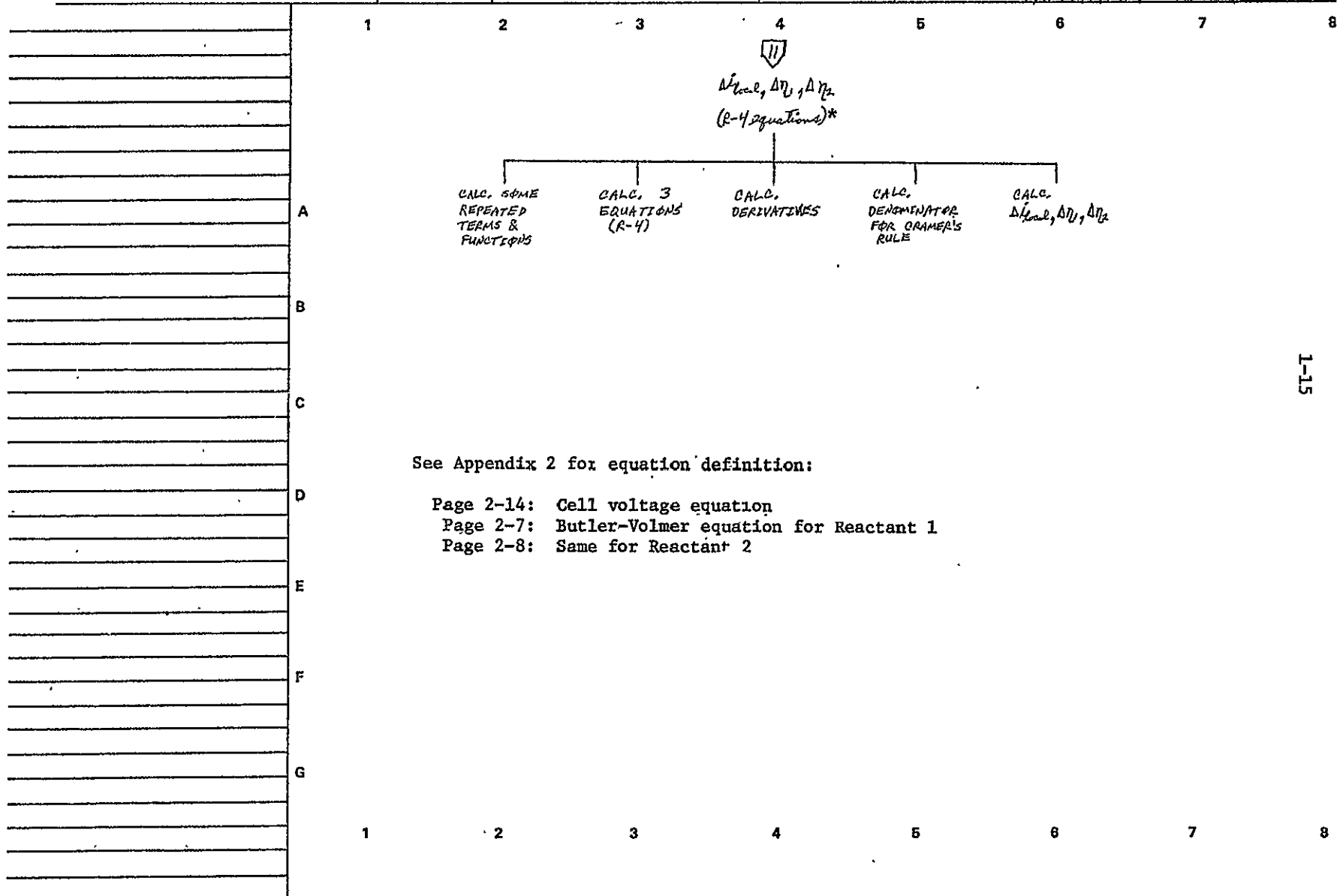


PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED	REFERENCE NO:	PAGE						
					<table border="1"> <tr> <th>MTWTFSS</th> <th>DAY</th> <th>YR</th> </tr> <tr> <td>11111</td> <td>11/11</td> <td>71</td> </tr> </table>	MTWTFSS	DAY	YR	11111	11/11	71	13	
MTWTFSS	DAY	YR											
11111	11/11	71											



# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTN	DAY	YR		
					11	29	78	14	



See Appendix 2 for equation definition:

Page 2-14: Cell voltage equation

Page 2-7: Butler-Volmer equation for Reactant 1

Page 2-8: Same for Reactant 2

# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	09	76	15	

$$1. XLAMDA = 10^3 * W * DX / FHRADV$$

$$2. XLMD1 = XLAMDA / (Z1 * QCELL1)$$

$$3. XLMD2 = XLAMDA / (Z2 * QCELL2)$$

$$4. XEI = ILCLX * EFC$$

$$5. XEI = ILCLX / EFD$$

$$6. DR1 = XLMD1 * XEI$$

$$DP1 = -DR1$$

$$7. DR2 = XLMD2 * XEI$$

$$DP2 = -DR2$$

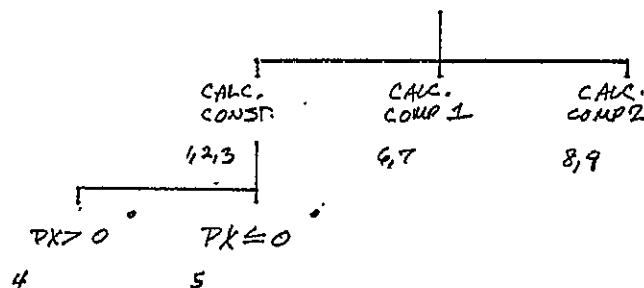
$$8. R1BAR = R1C + 0.5 * DR1$$

$$P1BAR = P1C + 0.5 * DP1$$

$$9. R2BAR = R2C + 0.5 * DR2$$

$$P2BAR = P2C + 0.5 * DP2$$

CONCENTRATION  
UPDATE



1-16

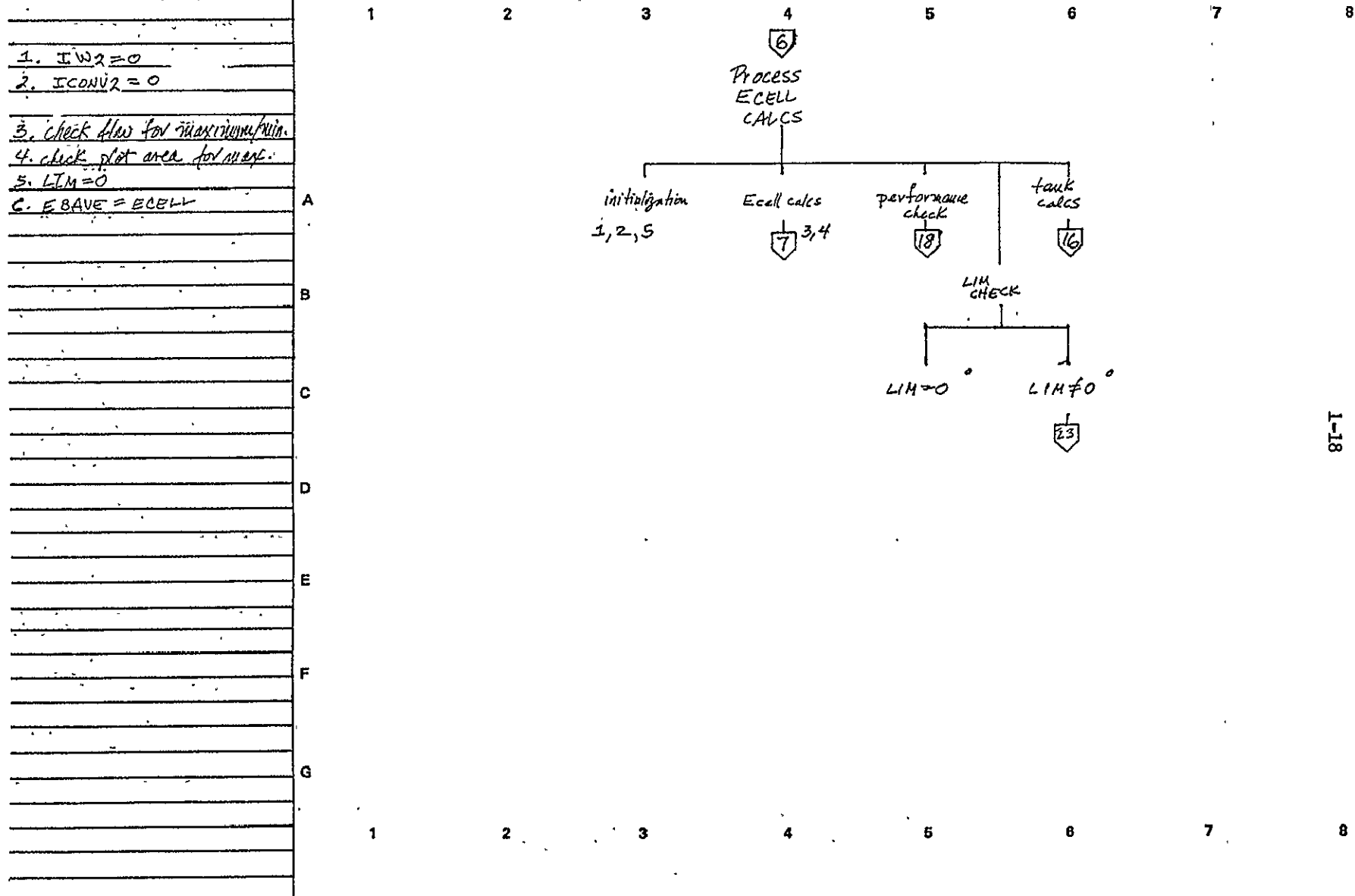
PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO: 16	PAGE OF
					MTH	DAY	YR		
					11	09	74		



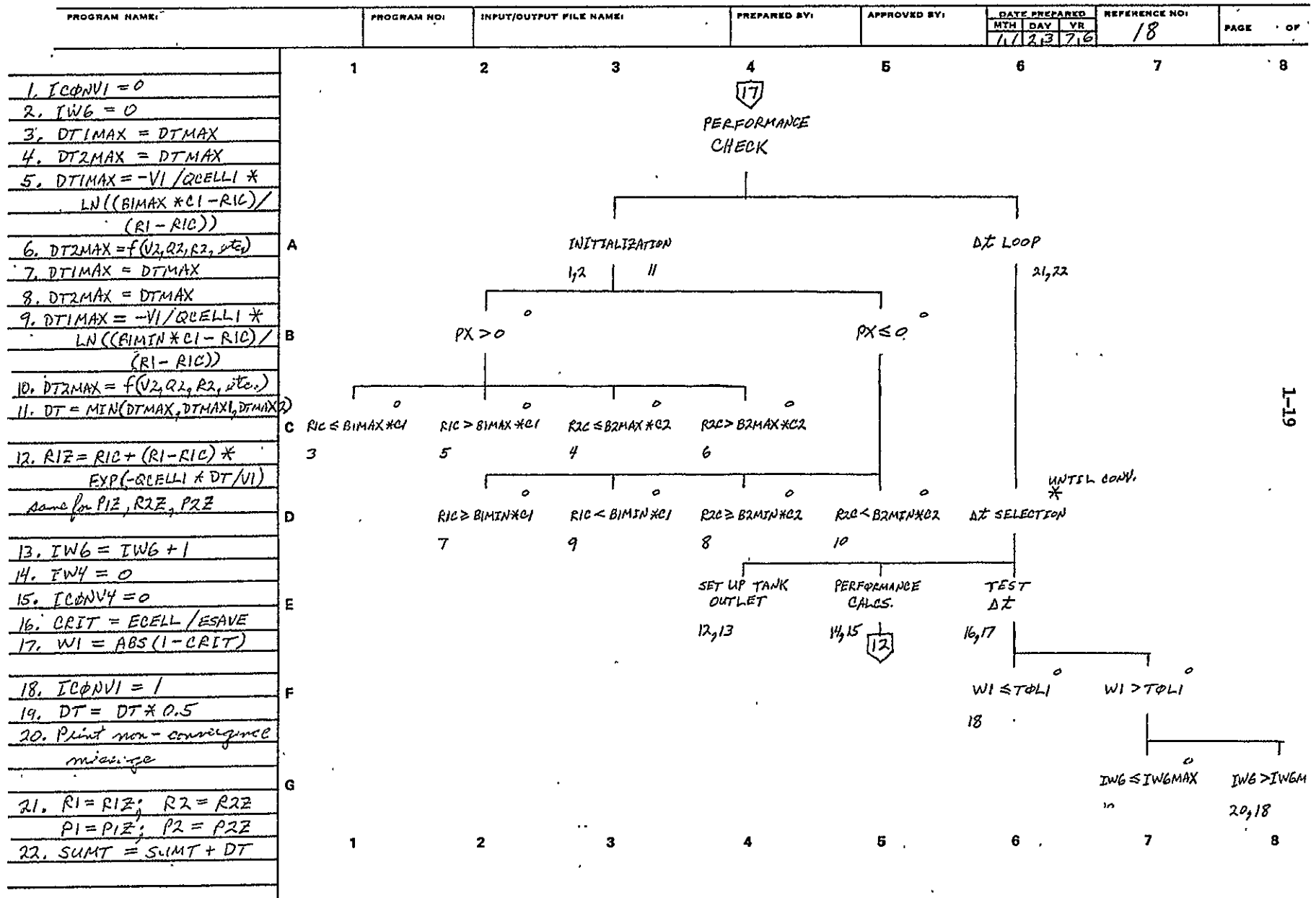


# EXXON MCS — PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		
					11	01	76	17	



EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM



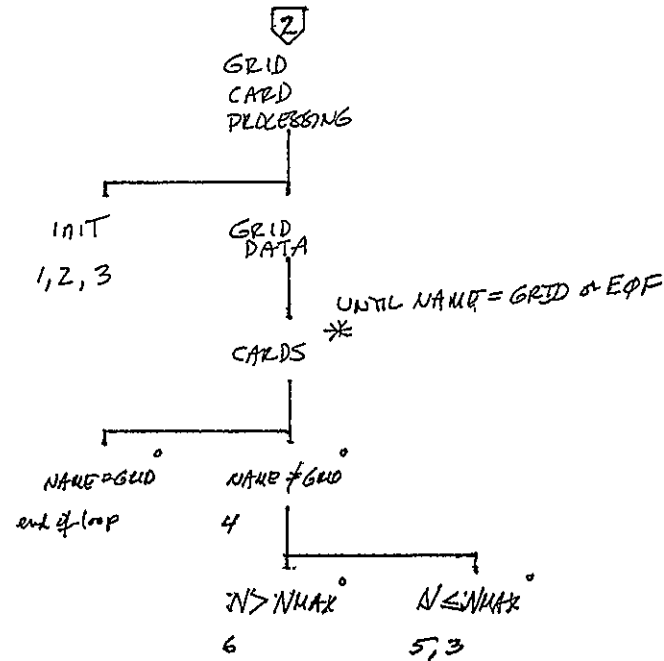
1-19

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO: 19	PAGE 01
					MTH	DAY	YR		
					11	01	76		

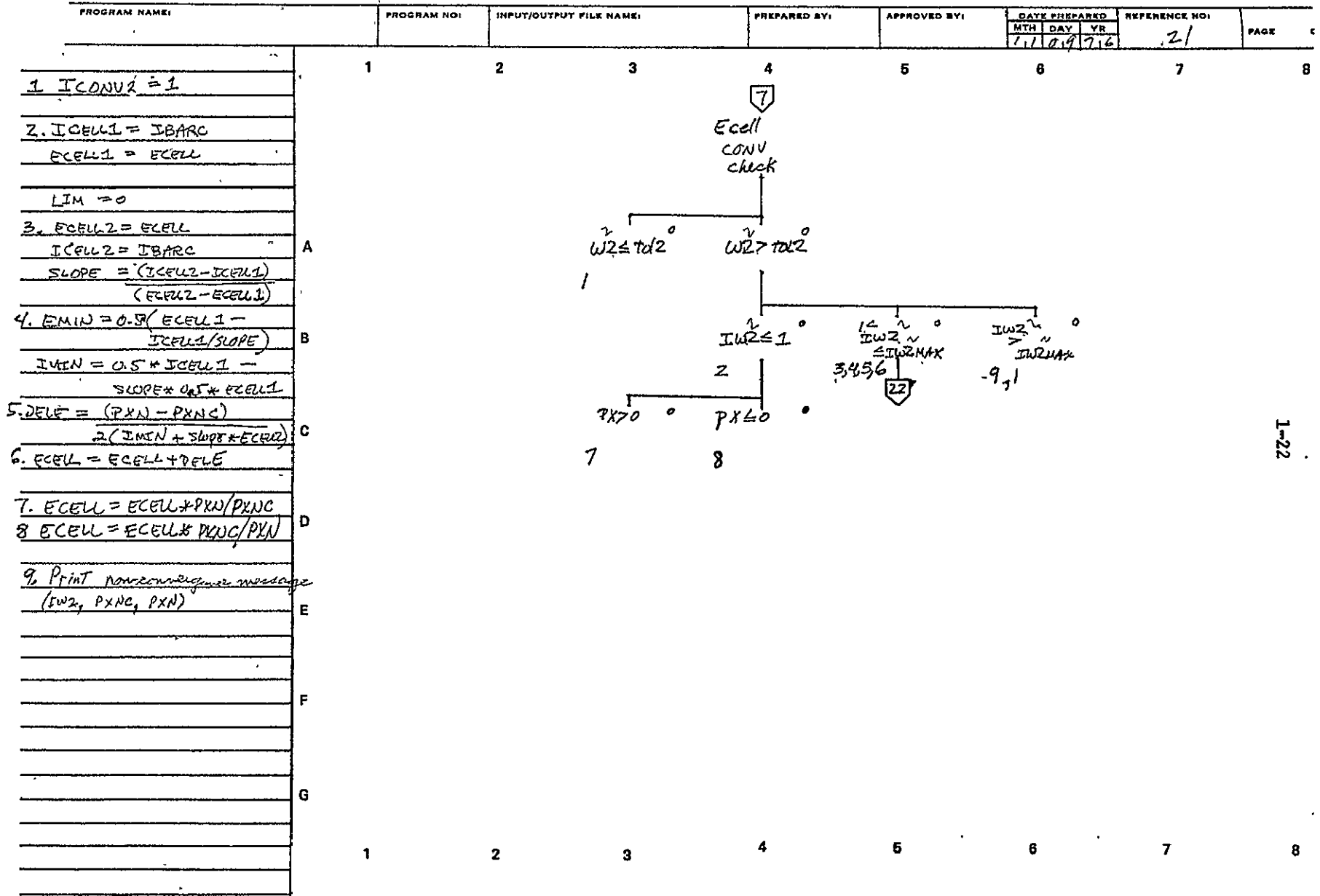


PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO: 20	PAGE 01
					MTH	DAY	YR		
					11	21	76		

6: print error message + STOP

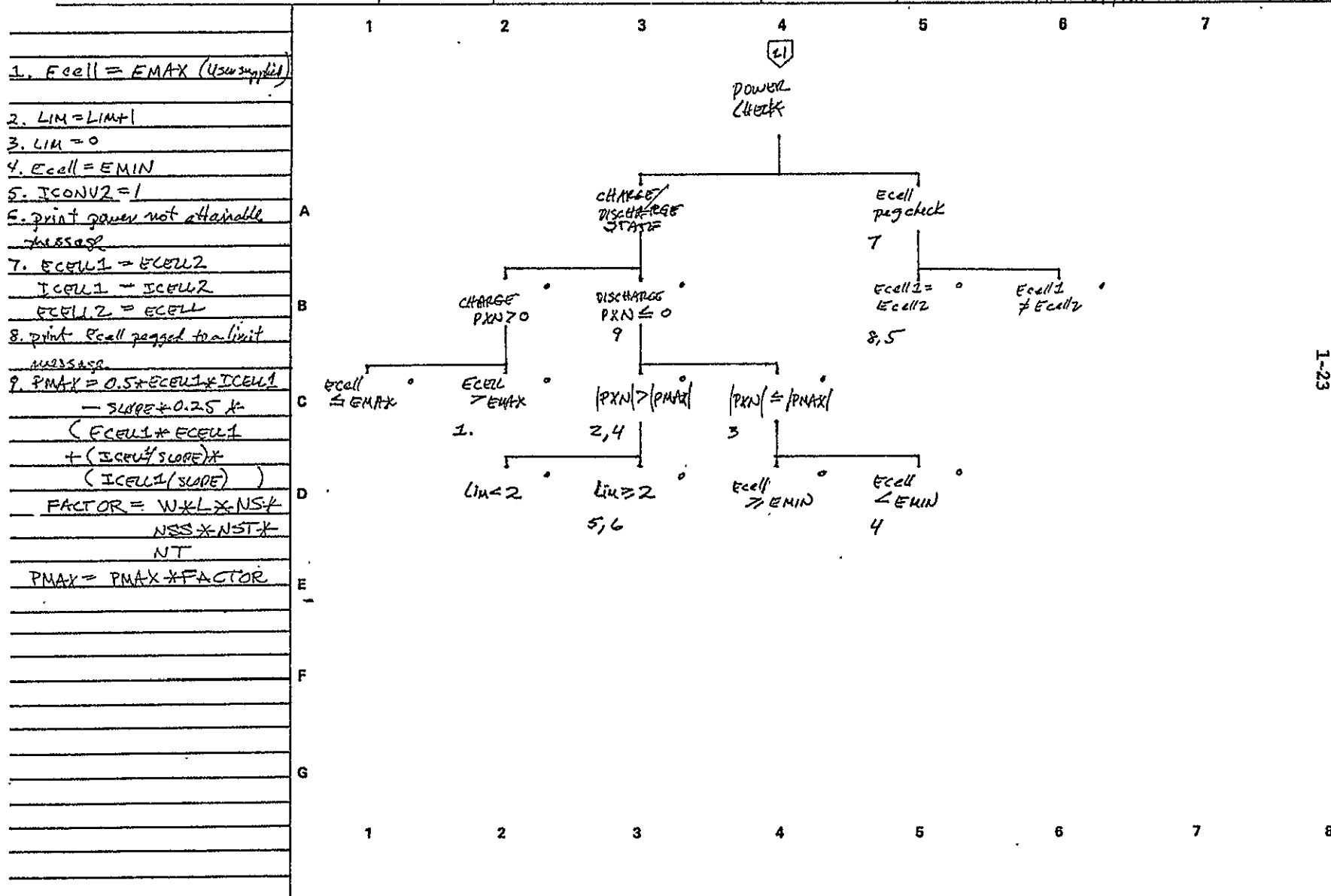


# EXXON MCS — PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM



# EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
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					11	08	76	22	



EXXON MCS - PROGRAM STRUCTURE DIAGRAM/DATA USAGE DIAGRAM

STDR-1

PROGRAM NAME:	PROGRAM NO:	INPUT/OUTPUT FILE NAME:	PREPARED BY:	APPROVED BY:	DATE PREPARED			REFERENCE NO:	PAGE
					MTH	DAY	YR		

1/1 1 716

23

PAGE

1 2 3 4 5 6 7 8

1.  $JX = SOUT + 60 * IT1 + IT2$   
 2.  $JX1 = JX / 60$   
 3.  $JX2 = JX - 60 * JX1$   
 4.  $J = J + 1$   
 5.  $IFROM1(J) = IT1$   
 6.  $IFROM2(J) = IT2$   
 7.  $IT1(J) = JX1$   
 8.  $IT2(J) = JX2$   
 9.  $IT1 = JX1$   
 10.  $IT2 = JX2$   
 11.  $POST(J) = PREDOX$   
 12.  $PDEMAND(J) = PX$   
 13.  $ISTAT1(J) = I1$   
 14.  $ISTAT2(J) = I2$   
 15.  $R1CONC(J) = (R1 - C24) / C24I$   
 16.  $R2CONC(J) = (R2 - C24) / C24I$

A

B

C

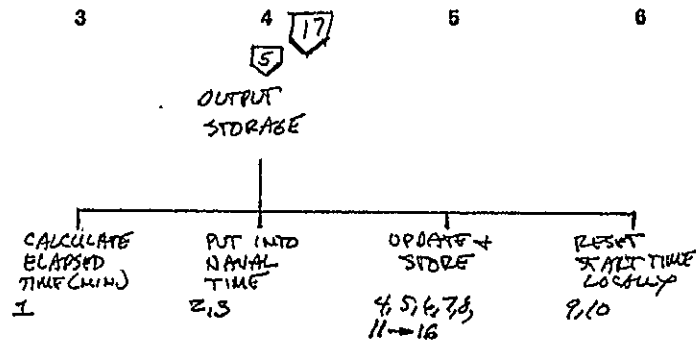
D

E

F

G

1 2 3 4 5 6 7 8



1-24

APPENDIX 2Outline of Computational Procedures Used in  
Stage 2 Model of Redox Energy Storage System

The following is a brief outline of the computational procedures used in the Stage 2 Model of Redox Energy Storage Systems. This outline presents the equations used, together with descriptive material, to assist the user of the Stage 2 Model computer program in interpreting the program operation. Details of the program parameters are given Attachment 1. Supplementary discussion of specific program software features is included elsewhere in the documentation package. This presentation relies heavily on the previously described Stage 1 Model, since many subroutines are common to both. It is assumed that the reader has this information available. (W. Erskine, Jr. and G. Ciprios, Task IIIA, "Documentation for Stage 1 Model Computer Program", June 23, 1976). The general layout of the Redox energy storage plant is the same for both models.

Stage 2 Model Overview

The Stage 2 Model is an expanded version of the Stage 1 and 1.5 Models. It is a load-following model capable of processing a user-supplied profile of discharge power and time requirements and charge power and time availability. Power profile variation is permitted over any time interval. Thus, the model can handle a wide range of potential utility operation.

The Stage 2 Model is limited to simulation. The user specifies an initial system estimate of reactant inventory and number of Redox converter trailers. The model carries out system operation as demanded, using the logic described below. Successfully completed cycles are sized and costed, using the Stage 1 model approach. Output signals are provided to guide the user if the required cycle requirements cannot be attained. Examples here include insufficient reactant supply and/or insufficient number of Redox converter trailers.

The model does not contain internal optimization routines to search for minimum cost combinations of reactant inventory and number of trailers. In effect, the user will carry out the optimization search by parametric variation of key input variables.



## System Performance Evaluation

### • Model Logic

At any time,  $t$ , the model attempts to match the required grid power level (discharge or charge), using instantaneous values for reactant composition. A nested series of logic loops is used, starting with:

- + Assumed value of time increment,  $\Delta t$
- + Assumed value of cell voltage,  $E_c$
- + Assumed value of auxiliary power,  $P_{aux}$ , including power conditioning efficiency and cooling fan, circulating pump and storage tank mixer horsepower.
- + Assumed value of average cell current density,  $\bar{i}$
- + Assumed value of path length increment through the Redox cell,  $\Delta x$
- + Assumed value of local current density required to satisfy electrochemical and mass transfer performance,  $i_{local}$ .

The nested loops are displayed in the simplified logic sequence shown in Table 1.

Evaluation of shuntage current losses, heating effects and flow rates are included at appropriate places within the loops. Initial estimate routines are provided for the assumed parameter values to speed convergence. Tolerance testing is provided, with tolerance limits set by the user, as indicated in Table 2. The approach is to provide a maximum opportunity for the user to modify the program in an intelligent manner, as experience and learning occur during subsequent program operation.

The performance calculation proceeds for a time increment,  $\Delta t$ , such that the variation in cell performance caused by changes in input reactant concentration is within a prescribed tolerance, or until  $P_{grid}$  changes. We assume a well-mixed reactant tankage system, with logic to handle multiple tank arrays.

Detailed program structure diagrams and logic diagrams for the Stage 2 Model are given in Appendix 1 and Table 1 of this volume.

The Redox cell configurations and dimensions are described later in Figures 4-12. The reader may wish to consult these figures to identify the structural features mentioned in the following discussion of Redox kinetic parameters.

Table 1

Simplified Logic Sequence for Redox System Performance Evaluation

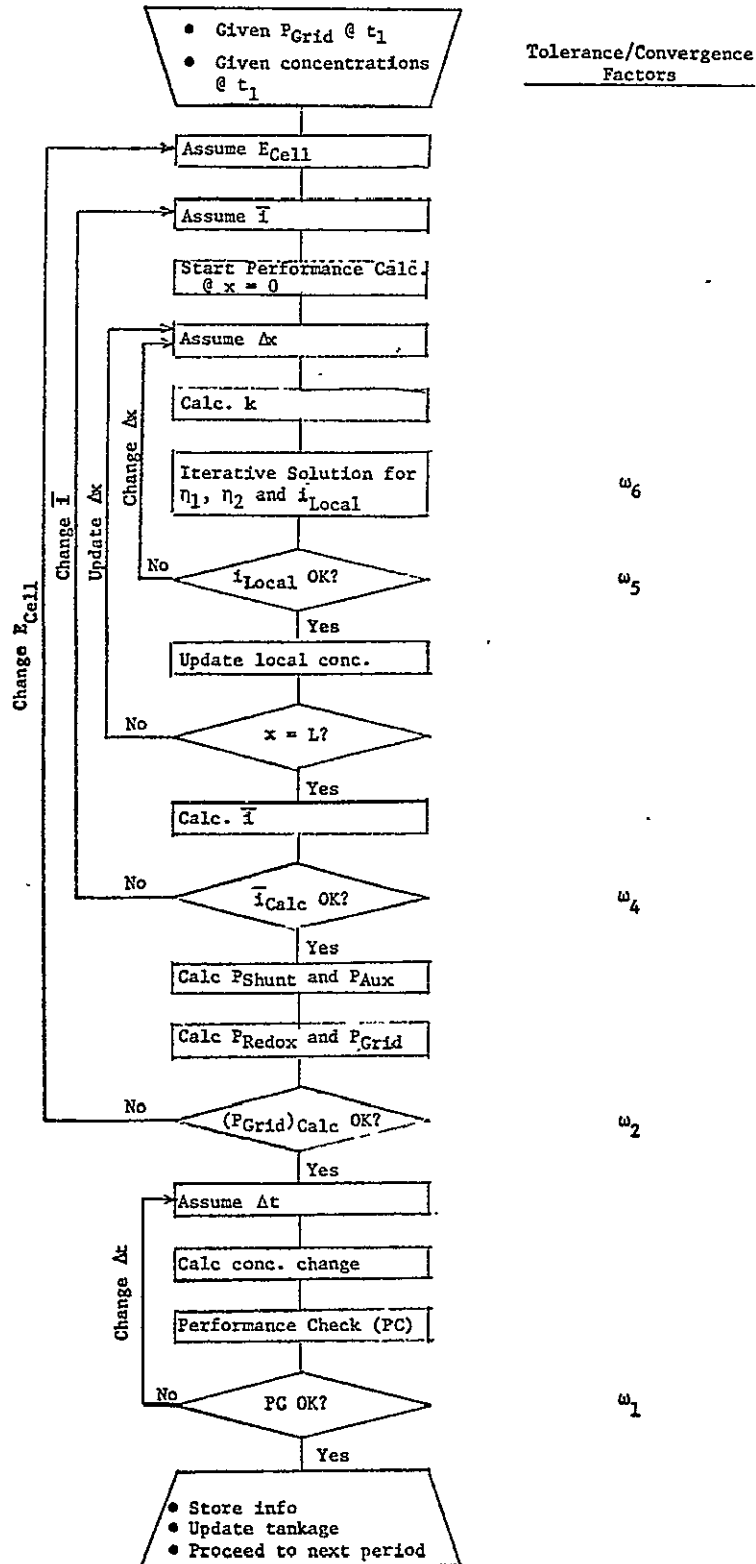


Table 2

Tolerance Limits for Iterative Loop Calculations

<u>Loop Parameter</u>	<u>Tolerance Factor Definition</u>	<u>Suggested Range of Tolerance Factor Values</u>
$\Delta t$	$\omega_1 = \left  1 - \frac{E_{\text{cell}}@t_2}{E_{\text{cell}}@t_1} \right $	0.01-0.1
$E_{\text{cell}}$	$\omega_2 = \left  1 - \frac{P_{\text{Grid Calc}}}{P_{\text{Grid Req'd}}} \right $	0.001-0.1
$\bar{i}$	$\omega_4 = \left  1 - \frac{\bar{i}_{\text{Calc}}}{\bar{i}_{\text{Assumed}}} \right $	0.01-0.1
$\Delta X$	$\omega_5 = \left  1 - \frac{i_{\text{Local}}@X_n}{i_{\text{Local}}@X_{n-1}} \right $	0.01-0.1
$i_{\text{Local}}$	$\omega_6 = [\text{See Below}]$	0.0001-0.001
$i_{\text{Load}}$	$\omega_7 = \left  1 - \frac{i_L \text{ Calc from Shunt Model}}{i_L \text{ Req'd from } \bar{i} \text{ Analysis}} \right $	0.01-0.1

## Notes:

- Tolerance  $\omega_6$  is a convergence criterion for the iterative simultaneous solutions for the local values of the electrochemical variables  $\eta_1$ ,  $\eta_2$  and  $i_{\text{Local}}$ .
- Tolerance  $\omega_3$  is unassigned.

• Redox Kinetics and Electrochemical Performance

This section summarizes the equations employed to describe the kinetics of soluble redox couple reactions. The potential-current conventions used are shown in Figure 1.

<u>Redox Half-Cell Reactions</u>	<u>Reaction Rates</u>	<u>Transfer Coefficients</u>
Couple 1: $R_1 + z_1 e \xrightleftharpoons[\text{Charge}]{\text{Discharge}} P_1$	$\xrightarrow{k_{R1}} \xleftarrow{k_{R1}}$	$\xrightarrow{\alpha_1} \xleftarrow{\alpha_1}$
Couple 2: $P_2 + z_2 e \xrightleftharpoons[\text{Discharge}]{\text{Charge}} R_2$	$\xrightarrow{k_{R2}} \xleftarrow{k_{R2}}$	$\xrightarrow{\alpha_2} \xleftarrow{\alpha_2}$

This convention was adopted to simplify the notation in the subsequent treatment of the modified Butler-Volmer equation that relates current density to electrode overpotential. As written, the cell should "spontaneously" discharge when the reactant (R) species of each couple are mixed. The notations for reaction rate constants,  $k_R$ , and transfer coefficients,  $\alpha$ , are also indicated. Additional discussion of  $\alpha$  is given below.

• Cell Potential (Voltage)

For charge or discharge, the cell potential,  $E_{\text{cell}}$ , is calculated from:

$$E_{\text{cell, volts}} = \Delta\phi + i R_{\text{eff}}$$

where:  $\Delta\phi$  = Difference in electrode potentials, volts  
 $i$  = (Geometric) current density, amp/cm<sup>2</sup>  
 $\bar{i}$  is average for total cell;  
 $i_L$  is local value at any point within cell  
 $R_{\text{eff}}$  = Membrane separator resistance, ohm-cm<sup>2</sup>

Again, the meaning of  $\Delta\phi$  and the sign convention adopted for the current density are shown in Figure 1. Continuing:

$$\Delta\phi = [(\phi_r)_1 + \eta_1] - [(\phi_r)_2 + \eta_2]$$

where:  $(\phi_r)_1 = (E^0)_1 + \frac{RT}{z_1 F} \ln \frac{(R_1)_b}{(P_1)_b}$

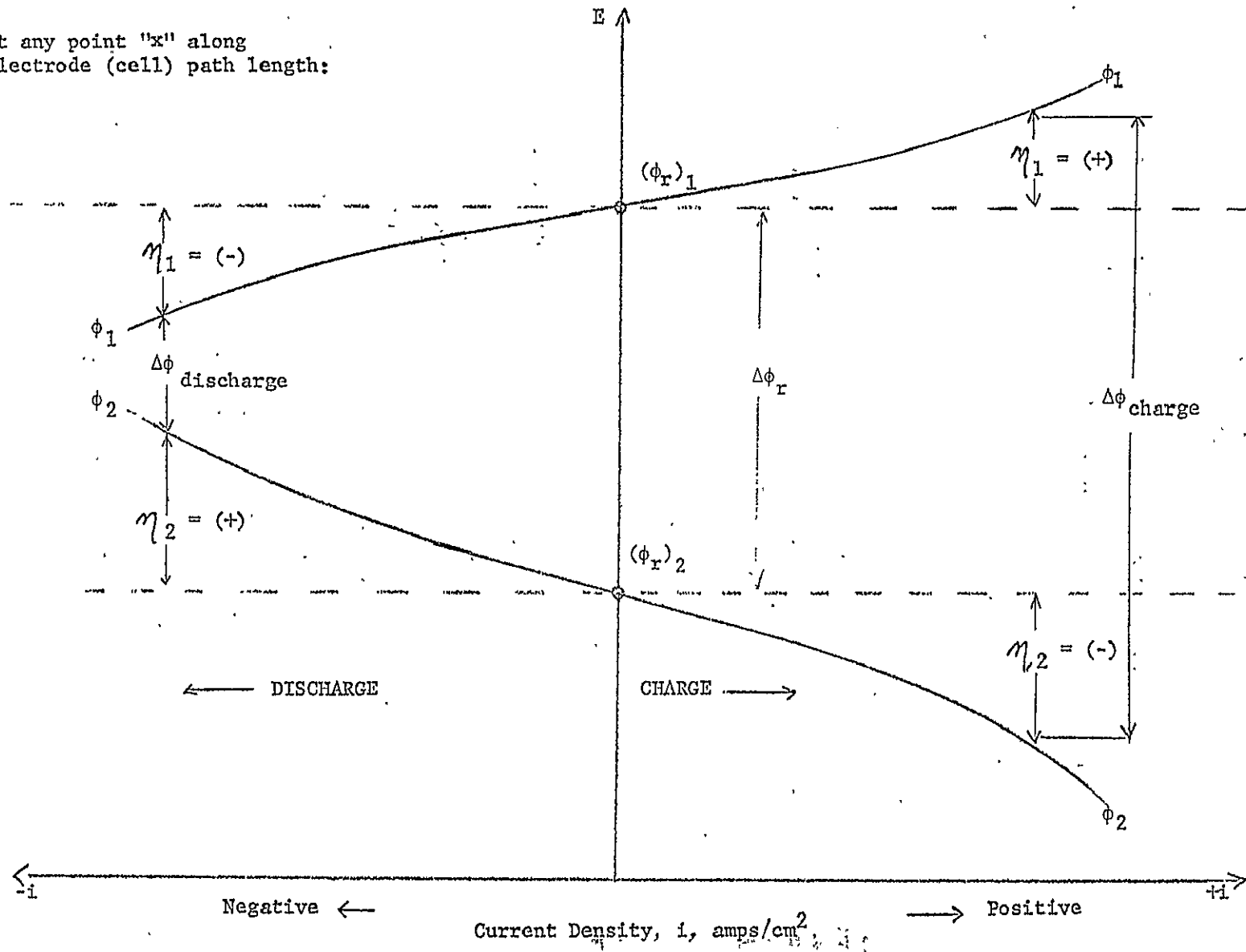
$$(\phi_r)_2 = (E^0)_2 - \frac{RT}{z_2 F} \ln \frac{(R_2)_b}{(P_2)_b}$$

$\phi_r$  = Local value of reversible electrode potential, volts  
 The meaning of  $\Delta\phi_r$  is shown in Figure 1

Figure 1

Redox Kinetics Potential-Current Conventions

At any point "x" along  
electrode (cell) path length:



- $E^0$  = Standard potential, measured at unity concentration for half cell reactants and products, volts. Assume  $(E^0)_1 > (E^0)_2$ .  
 $R$  = Gas constant,  $8.3 \frac{\text{volt amp sec}}{\text{gm mole } ^\circ\text{K}}$   
 $T$  = Absolute temperature,  $^\circ\text{K}$   
 $Z$  = Number of electrons involved in half cell reaction,  $\frac{\text{eq}}{\text{gm mole}}$   
 $F$  = Faraday's constant,  $96500 \frac{\text{amp sec}}{\text{eq}}$   
 $(R)_b$  = Local value of "reactant" bulk concentration,  $\frac{\text{gm moles}}{\text{liter}}$   
 $(P)_b$  = Local value of "product" bulk concentration,  $\frac{\text{gm moles}}{\text{liter}}$   
 $\eta$  = Electrode overpotential, volts

### • Electrode Overpotential

For charge or discharge, the local cell current density,  $i_L$ , is a function of local reactant and product concentrations, electrode overpotentials and reaction kinetic parameters, as shown in the following forms of the modified Butler-Volmer equations. The concentration gradients involved are depicted in Figure 2. These equations include terms to account for the presence of a flooded diffusion electrode deposit, using the approach described by Austin (Austin, L. G., "The Electrochemical Theory of Fuel Cells," chapter in Handbook of Fuel Cell Technology, C. Berger, ed., Prentice-Hall, Englewood Cliffs, N.J., 1968, p. 178).

Reactant Couple 1:

$$i_L = (i_o)_1' s_1 e_1 \left[ \frac{(P)_s}{(P)_b} \exp\left(\frac{\alpha_1 F}{RT} \eta_1\right) - \frac{(R)_s}{(R)_b} \exp\left(-\frac{\alpha_1 F}{RT} \eta_1\right) \right] \left[ \frac{\tanh e_1 \sqrt{K_1}}{e_1 \sqrt{K_1}} \right]$$

$$\text{where: } (i_o)_1' = (i_o)_1 \frac{(R)_s}{(R)_b} \frac{\alpha_1}{z_1} \frac{1 - \alpha_1}{z_1}$$

$i_o$  = Exchange current density, amps/geometric  $\text{cm}^2$ , a constant independent of local concentration.

$(R)_s, (P)_s$  = Reactant and product concentrations at local electrode surface, gm moles/liter

$(R)_b, (P)_b$  = Reactant and product concentrations in local bulk electrolyte, gm moles/liter. The relationships between surface and bulk composition are discussed below.

$$S_1 = (1-\epsilon_1) \rho_{\text{solid}(1)} \sigma_1 f_{c_1} 10^4, \text{ as defined in Attachment 1}$$

$$K_1 = \frac{(i_o)_1 S_1 q_1}{Z_1 D_1 \epsilon_1 F} \left[ \frac{\exp\left(\frac{\alpha_1^+ F}{RT} \eta_1\right)}{(P_1)_b} + \frac{\exp\left(-\frac{\alpha_1^- F}{RT} \eta_1\right)}{(R_1)_b} \right]$$

$\eta$  = Electrode overpotential, including activation and concentration overpotential, volts. The specific sign conventions adopted are shown in Figure 1.

Reactant Couple 2:

$$i_L = (i_o)_2 S_2 e_2 \left[ \frac{(P_2)_s}{(P_2)_b} \exp\left(-\frac{\alpha_2^+ F}{RT} \eta_2\right) - \frac{(R_2)_s}{(R_2)_p} \exp\left(\frac{\alpha_2^- F}{RT} \eta_2\right) \right] \left[ \frac{\tanh e_2 \sqrt{K_2}}{e_2 \sqrt{K_2}} \right]$$

$$\text{where: } (i_o)_2 = (i_o)_2 (R_2)_b^{\frac{1-\alpha_2^+}{z_2}} (P_2)_b^{\frac{\alpha_2^-}{z_2}}$$

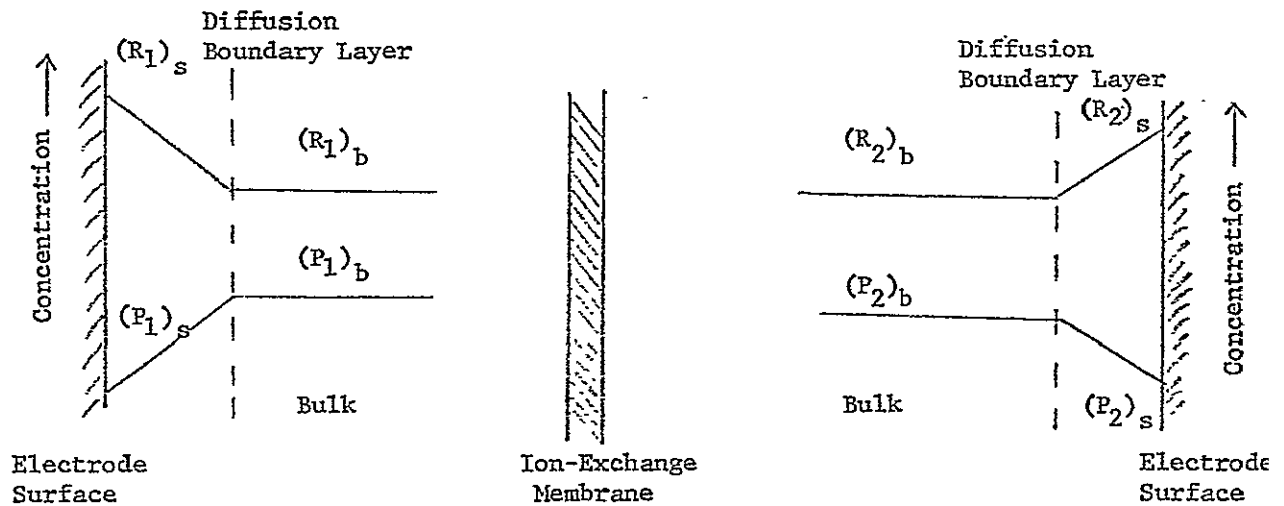
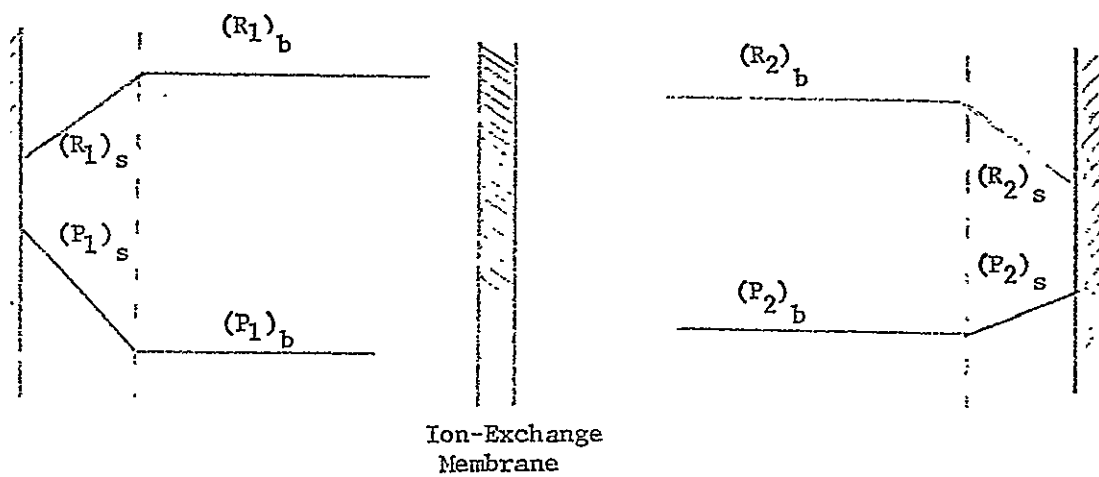
$$K_2 = \frac{(i_o)_2 S_2 q_2}{Z_2 D_2 \epsilon_2 F} \left[ \frac{\exp\left(-\frac{\alpha_2^+ F}{RT} \eta_2\right)}{(P_2)_b} + \frac{\exp\left(\frac{\alpha_2^- F}{RT} \eta_2\right)}{(R_2)_b} \right]$$

$$S_2 = (1-\epsilon_2) \rho_{\text{Solid}(2)} \sigma_2 f_{c_2} 10^4$$

The equations given above have assumed that species concentrations are equal to activities. It is also assumed that:

- + The same rate determining step exists for the charge and discharge reaction sequence.
- + The rate determining step involves an electron transfer.
- + The reduced and oxidized species of a redox couple have the same ionic diffusivity.

Figure 2

Local Concentration Gradients in Redox Cell OperationCharge CycleDischarge Cycle



- Exchange Current Density

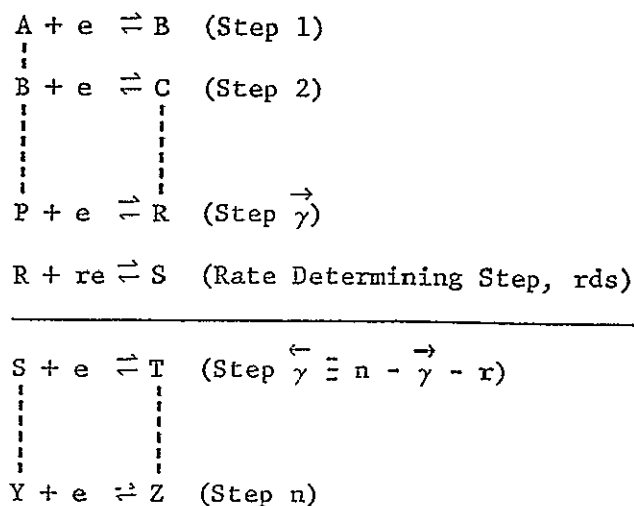
The geometric exchange current density,  $i_o$ , used in the Butler-Volmer equations presented above is a constant, independent of reactant and product concentrations. Literature values of  $i_o$  may, occasionally, have been obtained at non-standard concentrations  $[(R_1)_b \neq 1, (P_1)_b \neq 1]$ . The constant  $i_o$  may be derived from these non standard values, using the following equation:

$$(i_o)_{\text{model}} = (i_o)_{\text{lit}} (R_1)_b^{-\frac{\alpha_1}{z_1}} (P_1)_b^{-\left(1 - \frac{\alpha_1}{z_1}\right)}$$

where the relevant Redox equation is:  $R_1 + z_1 e \rightleftharpoons P_1$ .

- Transfer Coefficients

The following derivation, taken from Bockris and Reddy, Modern Electrochemistry, Plenum Press, New York, 1970, Chapters 8 and 9, can be used to estimate values of the transfer coefficient,  $\alpha$ . Consider a sequence of elementary steps comprising an overall Redox reaction:



Here,  $R + re \rightarrow S$  is the rate determining step, rds, preceeded by  $\vec{\gamma}$  single electron transfer steps and followed by  $\overleftarrow{\gamma}$  such steps. The rds consists of the transfer of  $r$  electrons. Note that  $r = 0$  represents a chemical rds and  $r = 1$  an electron transfer rds. Thus,  $n = \vec{\gamma} + \overleftarrow{\gamma} + r$ . It can be shown that the corresponding transfer coefficients,  $\alpha$ , are:

$$\overleftarrow{\alpha} = n - \vec{\gamma} - r\beta \quad (1)$$

$$\vec{\alpha} = \vec{\gamma} + r\beta \quad (2)$$

where  $\beta = A$  symmetry factor, generally found =  $1/2$ .

Adding Equations (1) and (2) yields:

$$\overleftarrow{\alpha} + \vec{\alpha} = n$$

The possible values of transfer coefficients estimated by this analysis are tabulated below, assuming  $\beta = 1/2$  and  $r = 1$  (the rds involves an electron transfer):

$n$	$\vec{\gamma}$	$\overleftarrow{\gamma}$	$\vec{\alpha}$	$\overleftarrow{\alpha}$
1	0	0	1/2	1/2
2	1	0	3/2	1/2
2	0	1	1/2	3/2
3	2	0	5/2	1/2
3	1	1	3/2	3/2
3	0	2	1/2	5/2

Example 1:  $\text{Fe}^{+3} + e \rightarrow \text{Fe}^{+2}$

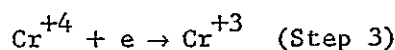
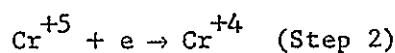
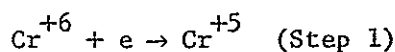
Here,  $n = 1$ ,  $\beta = 1/2$  and  $r = 1$ , assuming the rds involves an electron transfer. Thus,  $n - r = 1 - 1 = 0 = \vec{\gamma} + \overleftarrow{\gamma}$ . But the latter must be integers, such that  $\gamma \geq 0$ . Therefore,  $\vec{\gamma} = \overleftarrow{\gamma} = 0$ , and:

$$\vec{\alpha} = \vec{\gamma} + r\beta = 0 + (1)(1/2) = 1/2$$

$$\overleftarrow{\alpha} = n - \vec{\gamma} - r\beta = 1 - 0 - (1)(1/2) = 1/2$$

Example 2:  $\text{Cr}^{+6} + 3e \rightarrow \text{Cr}^{+3}$

Here,  $n = 3$ ,  $\beta = 1/2$  and  $r = 1$ . The reaction sequence might be:



Possible transfer coefficient values are listed below:

Reds	n	$\alpha$	$\beta$	$\gamma$	$\delta$	$\epsilon$
Step 1	3	1	0	2	1/2	5/2
Step 2	3	1	1	1	3/2	3/2
Step 3	3	1	2	0	5/2	1/2

Additional discussion of the symmetry factor and transfer coefficient can be found in: Bockris and Nagy, J. Chem. Ed. 50 839 (1973).

#### • Surface-Bulk Concentration Relations

The concentrations of reactants and products at the electrode surface can be related to those in the bulk electrolyte, assuming the presence of a local diffusion boundary layer and Fick's law diffusion across this layer.

$$\frac{(R_1)_s}{(R_1)_b} = 1 + \frac{1000 i_L}{Z_1 \Psi_1 k_1 F (R_1)_b}$$

$$\frac{(P_1)_s}{(P_1)_b} = 1 - \frac{1000 i_L}{Z_1 \Psi_1 k_1 F (P_1)_b}$$

$$\frac{(R_2)_s}{(R_2)_b} = 1 + \frac{1000 i_L}{Z_2 \Psi_2 k_2 F (R_2)_b}$$

$$\frac{(P_2)_s}{(P_2)_b} = 1 - \frac{1000 i_L}{Z_2 \Psi_2 k_2 F (P_2)_b}$$

where:  $k$  = Local mass transport rate, cm/sec, discussed below.

$$= \frac{D}{\delta}$$

$D$  = Ionic diffusion coefficient,  $\text{cm}^2/\text{sec}$

$\delta$  = Diffusion boundary layer thickness, cm. Note that  $\delta$  may be different in charge or discharge operation, depending on local hydrodynamic factors, including flow rates.

#### • Mass transfer Coefficients

Mass transfer coefficients for each Redox couple are calculated using correlations developed by U. Landau and C.W. Tobias (Electrochemical Society Extended Abstracts for May, 1976 meeting, Washington D.C., p. 663).

+ Calculate Reynolds Number:

$$Re = \frac{d_h v \rho_{sol}}{\mu}$$

where:  $d_h$  = Hydraulic diameter, cm =  $\frac{2\tau\omega}{\tau+\omega}$

$$v = \text{Solution velocity, } \frac{\text{cm}}{\text{sec}} = \frac{Q_{cell}}{\tau\omega}$$

$$\rho_{sol} = \text{Solution density, } \frac{\text{gm}}{\text{cm}^3}$$

$\mu$  = Solution viscosity, poise

$$Q_{cell} = \text{Volumetric flow rate, } \frac{\text{cm}^3}{\text{sec}} = \frac{f\omega L \int_0^1 \frac{1}{Z F(R)} dx}{\int_0^1 \frac{1}{Z F(P)} dx} \text{ or } \frac{f\omega L \int_0^1 \frac{1}{Z F(R)} dx}{\int_0^1 \frac{1}{Z F(P)} dx}$$

(Additional discussion of Q is presented below).

+ Calculate mass transfer coefficient:

$$\text{- If } Re \leq 2800: k = \left(\frac{D}{d_h}\right) 1.247 \left(Re Sc \frac{d_h}{x}\right)^{0.331}$$

$$\text{- If } 2800 < Re \leq 12000: k = \left(\frac{D}{d_h}\right) 0.067 Re^{0.75} Sc^{0.333} \left(\frac{d_h}{x}\right)^{0.3}, \text{ for } x < 0.73 d_h$$

$$k = \left(\frac{D}{d_h}\right) 0.0113 Re^{0.87} Sc^{0.35}, \text{ for } x > 0.73 d_h$$

$$\text{- If } Re > 12000: k = \left(\frac{D}{d_h}\right) 0.067 Re^{0.75} Sc^{0.333} \left(\frac{d_h}{x}\right)^{0.3}, \text{ for } x \leq 0.73 d_h$$

$$k = \left(\frac{D}{d_h}\right) 0.010 Re^{0.92} Sc^{0.336}, \text{ for } x > 0.73 d_h$$

where:  $Sc$  = Schmidt number =  $\frac{\mu}{\rho D}$

$x$  = Distance down cell from entry point, cm.

+ A factor,  $\Psi$ , is added to modify the calculated value of  $k$ :  $k_{\text{effective}} = \Psi k_{\text{calculated}}$ . This factor can be used to simulate the effect of eddy promotion devices added within the solution flow cavity.

• Redox Cell Material Balance

This section presents the equations and general computational approach used to carry out the Redox cell material balance. The following equation is used to calculate the cell voltage at any point in the cell ( $E_c$  is assumed to be constant along the electrode path length):

$$E_c = \left[ (E^o)_1 - (E^o)_2 \right] + \frac{RT}{F} \ln \left[ \frac{(R_1)_b}{(P_1)_b} \right]^{\frac{1}{Z_1}} \left[ \frac{(R_2)_b}{(P_2)_b} \right]^{\frac{1}{Z_2}} + \left[ \eta_1 - \eta_2 \right] + i R_{eff}$$

Material balance equations are used to describe the local changes of composition within the Redox cell during operation. Referring to Figure 3, for a local cell segment of length  $\Delta x$ , the following equations describe the changes in reactant and product composition passing thru the segment:

$$\left[ (R_1)_{b, x+\Delta x} - (R_1)_{b, x} \right] \equiv \Delta(R_1)_b = \frac{\lambda_1 i_L}{E_{FD}} \text{ on discharge; } E_{FC} \lambda_1 i_L \text{ on charge}$$

$$\left[ (P_1)_{b, x+\Delta x} - (P_1)_{b, x} \right] \equiv \Delta(P_1)_b = \frac{-\lambda_1 i_L}{E_{FD}} \text{ on discharge; } -E_{FC} \lambda_1 i_L \text{ on charge}$$

and, similarly:

$$\Delta(R_2)_b = \frac{\lambda_2 i_L}{E_{FD}} \text{ on discharge; } E_{FC} \lambda_2 i_L \text{ on charge}$$

$$\Delta(P_2)_b = \frac{-\lambda_2 i_L}{E_{FD}} \text{ on discharge; } -E_{FC} \lambda_2 i_L \text{ on charge}$$

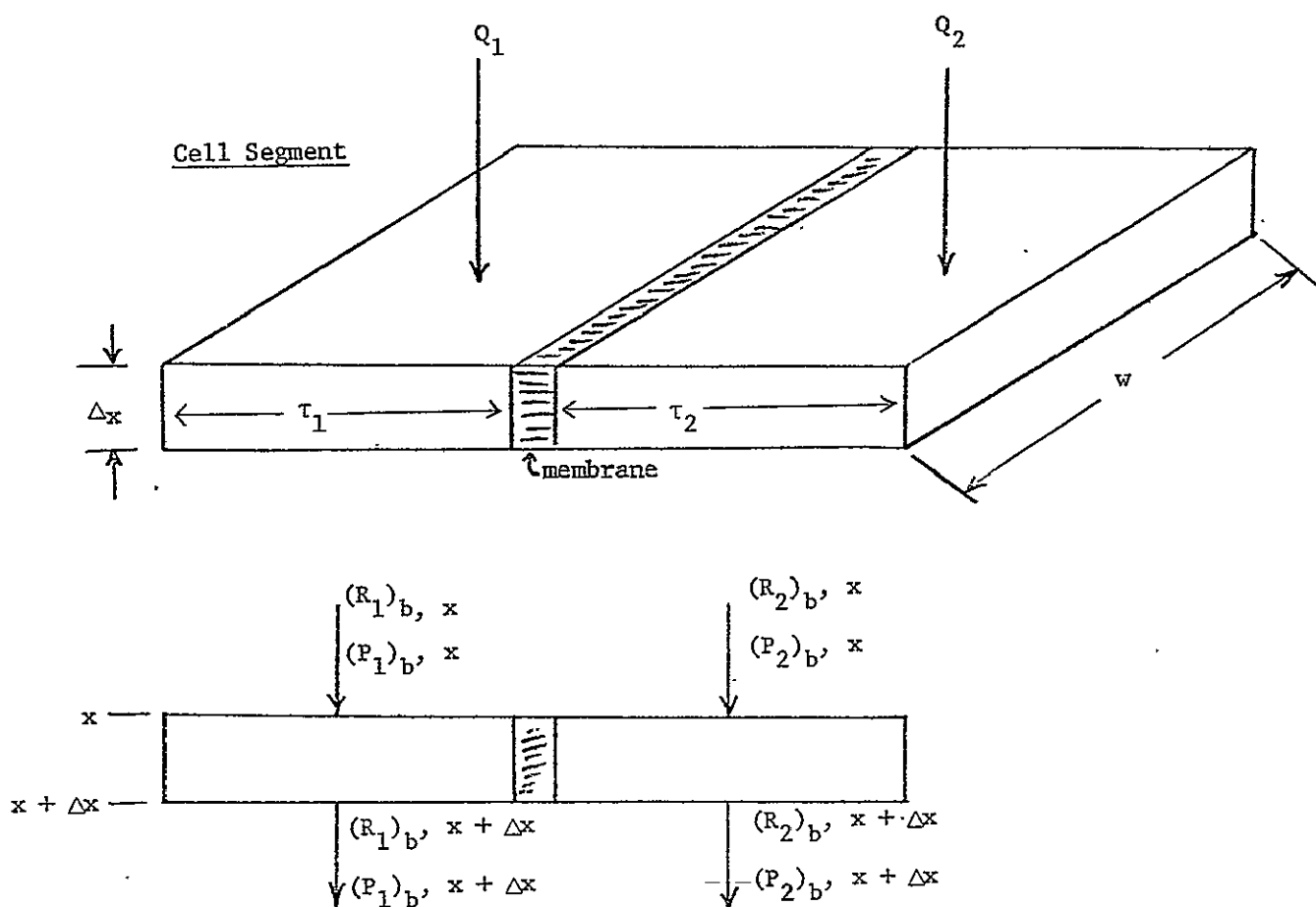
$$\text{where: } \lambda_1 = \frac{1000 \omega \Delta x}{Z_1 F Q_1}$$

$$\lambda_2 = \frac{1000 \omega \Delta x}{Z_2 F Q_2}$$

$$i_L = \text{Local current density, amps/cm}^2$$

$E_{FD}, E_{FC}$  = Faradaic efficiencies during discharge and charge, assumed to be constants, applicable to both reactant couples.

Figure 3

Redox Cell Material Balances

In general:

$$[(R_1)_b, x + \Delta x - (R_1)_b, x] = \frac{1000 i_L w \Delta x}{z_1 F Q_1}$$

where:  $(R_1)_b$  = Reactant bulk concentration, gm moles/liter  
 $1000$  =  $\text{cm}^3/\text{liter}$   
 $Q_1$  = Solution flow rate,  $\text{cm}^3/\text{sec}$   
 $i_L$  = Current density,  $\text{amps}/\text{cm}^2$   
 $w$  = Cell width, cm  
 $\Delta x$  = Segment length, cm  
 $z_1$  = Equivalents/gm mole  
 $F$  = Faraday's constant, 96500 amp sec/eq.

The following general computational procedure is used to calculate the Redox cell operation:

- + Fix a value for  $E_{\text{cell}}$ , assumed constant along the length of the cell. The cell geometry and reactant flow rates are assumed to be known. The inlet species concentrations are assumed known, but will vary with time. The procedure used to establish the flow rates is described below.
- + Select a local value of current density,  $i_L$ , assumed constant along a cell length increment  $\Delta x$ .
- + Calculate the local changes in species concentrations, using the equations given above.
- + Calculate the average segment species concentrations:

$$(\bar{R}_1)_b = (R_1)_{b,o} + \frac{\Delta(R_1)_b}{2}$$

$$(\bar{P}_1)_b = (P_1)_{b,o} + \frac{\Delta(P_1)_b}{2}$$

$$(\bar{R}_2)_b = (R_2)_{b,o} + \frac{\Delta(R_2)_b}{2}$$

$$(\bar{P}_2)_b = (P_2)_{b,o} + \frac{\Delta(P_2)_b}{2}$$

- + Calculate the local values of  $\eta_1$  and  $\eta_2$  using the Butler-Volmer equations and the average species concentrations. Note that iterative procedures will be required.
- + Calculate a predicted value of  $E_{\text{cell}}$  using the complete voltage equation, the average compositions and values calculated above.
- + Compare  $(E_{\text{cell}})_{\text{predicted}}$  with  $(E_{\text{cell}})_{\text{fixed}}$ . If values agree within a predetermined tolerance, local cell segment balance is complete. If not, select another local value of  $i_L$  and repeat. Continue until adequate  $(E_{\text{cell}})$  match is obtained.

- + Calculate segment outlet concentrations, based on final value of local  $i_L$ . Repeat calculation for next cell segment, using these concentrations as inlet. Tabulate  $i_L$  values.
  - + Proceed down the cell length, as above.
  - + This procedure will yield the local variation of  $i$  with distance down the cell. An average value of current density,  $\bar{i}$ , is calculated, for evaluation of other system characteristics.
  - + The procedure is repeated until the value of  $E_c$  is achieved that satisfies the grid power requirement.
  - + This procedure is repeated at a later time,  $t+\Delta t$ , where the cell inlet compositions have changed significantly.
- Solution Flow Rates, Reactant Concentrations and Utilization

The preceding calculations require values for the concentration of Redox couple species in the reactant form (R) and product form (P). Initial tank inventory values are related to the total concentration of Redox couple species 1 and 2 via:

$$(R_1)_{b,Initial} = (\beta_{MAX})_1 C_1 \text{ and } (P_1)_{b,Initial} = C_1 - (R_1)_{b,Initial}$$

$$(R_2)_{b,Initial} = (\beta_{MAX})_2 C_2 \text{ and } (P_2)_{b,Initial} = C_2 - (R_2)_{b,Initial}$$

where: C = Total redox couple species concentration, gm moles/liter  
(an input parameter)

$\beta$  = Concentration limit factors

Note that upper and lower concentration limits can be assumed; with appropriate input parameters:  $\beta_{MAX 1}$ ,  $\beta_{MIN 1}$  and  $\beta_{MAX 2}$ ,  $\beta_{MIN 2}$ .

These factors are related to the "utilization" factor,  $u$ , used in the Stage 1 Model via:

$$u_1 = (\beta_{MAX})_1 - (\beta_{MIN})_1$$

$$u_2 = (\beta_{MAX})_2 - (\beta_{MIN})_2$$

These limits are imposed on the composition of the reactant storage tanks, not during the internal Redox cell calculations. At any time, the flow output concentration of the Redox cell is constrained to be greater than or equal to zero.



The preceding calculations also require a value for solution flow rate within a Redox cell,  $Q$ . The Stage 2 Model selects solution flow rates as some pre-determined multiple of the stoichiometric flow rate, based on the average value of Redox-cell current density,  $\bar{i}$ . Thus:

$$(Q_{\text{cell}})_1 = \frac{f_1 w L |\bar{i}| 10^3}{Z_1 F (R_1)_{b,x=0}} \quad (\text{discharge}) = \frac{f_1 w L \bar{i} 10^3}{Z_1 F (P_1)_{b,x=0}} \quad (\text{charge})$$

$$(Q_{\text{cell}})_2 = \frac{f_2 w L |\bar{i}| 10^3}{Z_2 F (R_2)_{b,x=0}} \quad (\text{discharge}) = \frac{f_2 w L \bar{i} 10^3}{Z_1 F (P_2)_{b,x=0}} \quad (\text{charge})$$

where  $f$  = Solution flow rate factor (an input parameter), analogous to the corresponding term in the Stage 1 Model.

#### • Shuntage Current Loss

The power loss associated with shuntage (leakage) currents flowing thru common electrolyte paths within the Redox stack is calculated during every  $\Delta t$  time increment. This loss is treated as an equivalent auxiliary power loss. The computational model is a modified form of the procedure developed by P. Prokopius of NASA-Lewis (Prokopius, P.R., "Model for Calculation Electrolytic Shunt Path Losses in Large Electrochemical Energy Conversion Systems," NASA TM X-3359, April, 1976). The model is used for the series-connected substack assembly, using the average cell current density,  $\bar{i}$ , as load current. Shunt current paths in the anolyte and catholyte manifolds between substacks within a stack are neglected. Also, shuntage current losses between stacks and between trailers are neglected.

The following procedure is used to compute the required sub-routine input data, using the Stage 2 Model notations and cell designs described elsewhere in this documentation package.

+ Calculate cell reversible potential:

$$e, \text{ volts} = \Delta\phi_R = (E_1^\circ - E_2^\circ) + \frac{RT}{F} \ln \left[ \frac{(\bar{R}_1)_b}{(\bar{P}_1)_b} \right]^{\frac{1}{Z_1}} + \frac{RT}{F} \ln \left[ \frac{(\bar{R}_2)_b}{(\bar{P}_2)_b} \right]^{\frac{1}{Z_2}}$$

where:  $\bar{R}, \bar{P}$  = Arithmetic average concentration between cell inlet and outlet

+ Calculate equivalent load current:

$$i_L, \text{ amps.} = \bar{i} w L$$

+ Calculate equivalent cell internal resistance:

$$R_i, \text{ ohms} = \frac{\rho \delta}{w L}$$

- + Calculate port electrolytic resistance (equivalent to NASA model  $R_A$  and  $R_C$ ):

$$\bar{R}_{\text{PORT}(1)} = \frac{R_{\text{PORT}(1)}}{np_1} \quad ; \quad \bar{R}_{\text{PORT}(2)} = \frac{R_{\text{PORT}(2)}}{np_2}$$

$$R_{\text{PORT}(1)} = \frac{\rho_{\text{E}(1)} (\ell_2 + \ell_3)}{(pw_1)(ph_1)} \quad ; \quad R_{\text{PORT}(2)} = \frac{\rho_{\text{E}(2)} (\ell_2 + \ell_5)}{(pw_2)(ph_2)}$$

- + Calculate manifold electrolytic resistance (equivalent to NASA model  $R_{AM}$  and  $R_{CM}$ ):

$$\bar{R}_{\text{MANIF}(1)} = \frac{R_{\text{MANIF}(1)}}{nm_1} \quad ; \quad \bar{R}_{\text{MANIF}(2)} = \frac{R_{\text{MANIF}(2)}}{nm_2}$$

$$R_{\text{MANIF}(1)} = \frac{\rho_{\text{E}(1)} (\delta + \gamma_c + e_1 + e_2 + \tau_1 + \tau_2)}{(ml_1)(mw_1)}$$

$$R_{\text{MANIF}(2)} = \frac{\rho_{\text{E}(2)} (\delta + \gamma_c + e_1 + e_2 + \tau_1 + \tau_2)}{(ml_2)(mw_2)}$$

- + Calculate an initial guess of the equivalent load resistance required in the iterative calculation to ensure that the derived value of  $i_L$  is achieved:

$$(R_L)_{\text{Initial, ohms}} = \frac{n E_c}{i w L}$$

#### • Auxiliary Power Loss

Auxiliary power losses are estimated during each  $\Delta t$  time interval. These losses are used to modify the gross power level of the Redox converter to ensure that the required net power level is delivered to the utility grid during discharge (or received from the grid during charge). The individual components making up the auxiliary power loss are described below:

- + Shuntage power loss - obtained from the shunt current sub-routine in the Stage 2 Model.
- + Pumping losses - estimated using the instantaneous value of pump flow rate capacity. Power requirement is based on Stage 1 Model value (Documentation, page 1-18, Figure 5). A factor,  $f_p$ , is introduced to modify the estimated pumping horsepower.
- + Tank mixer power loss - estimated using the user specified tankage arrangement. Power requirement is based on Stage 1 Model value.
- + Cooler fan power loss - obtained from the instantaneous value of fan horsepower calculated in the cooler sub-routine of the Stage 2 Model.

### Redox Converter Section

This section consists of installed, shippable trailers containing Redox converter stacks. A parallel plate, filter press assembly is assumed for the Redox stacks, using bipolar collectors, flow-by electrodes and cocurrent reactant flow. The user specifies the cell, stack and trailer design, using the structures shown in Figures 4 to 12 as a basis. Internal dimension checks are carried out to ensure a consistent design. These checks are given in Table 3. In addition to the cell size, the user specifies the number of cells in a substack (series electrical) and substacks in a stack (parallel electrical). Assembly within a trailer configuration is included, together with appropriate stack electrical hookup.

#### • Stack Component Size

+ Calculate volume of plastic in end plates:

$$v_{EPPA}, \text{cm}^3 = [\omega + 2(\omega_2 + \omega_3)] [L + 2(\ell_2 + \ell_3 + \ell_4 + m\ell_1)] \gamma_{EP(A)} \\ - [(nm_1)(m\omega_1)(m\ell_1) + (nm_2)(m\omega_2)(m\ell_2)] \gamma_{EP(A)}$$

$$v_{EPPB}, \text{cm}^3 = \text{as above, with } \gamma_{EP(B)} \text{ substituted for } \gamma_{EP(A)}$$

+ Calculate volume of sub stack end plate plastic (A):

$$v_{SSEPA}, \text{cm}^3 = [\omega + 2(\omega_2 + \omega_3)] [L + 2(\ell_2 + \ell_3 + \ell_4 + m\ell_1)] \gamma_{SSEP(A)} \\ - 2[(nm_1)(m\omega_1)(m\ell_1) + (nm_2)(m\omega_2)(m\ell_2)] \gamma_{SSEP(A)} \\ - \omega L \gamma_{SSEPC} - (\omega_2 + \omega_3) \ell_T \gamma_T$$

+ Calculate volume of substack end plate plastic (B):

$$v_{SSEPB}, \text{cm}^3 = [\omega + 2(\omega_2 + \omega_3)] [L + 2(\ell_2 + \ell_3 + \ell_4 + m\ell_1)] \gamma_{SSEP(B)} \\ - 2[(nm_1)(m\omega_1)(m\ell_1) + (nm_2)(m\omega_2)(m\ell_2)] \gamma_{SSEP(B)} \\ - (\omega + 2\omega_2)(L + 2\ell_2) \gamma_c - \omega L \gamma_{SSEPC} - (\omega_2 + \omega_3) \ell_T \gamma_T$$

Figure 4

Isometric View of Assembled Stack

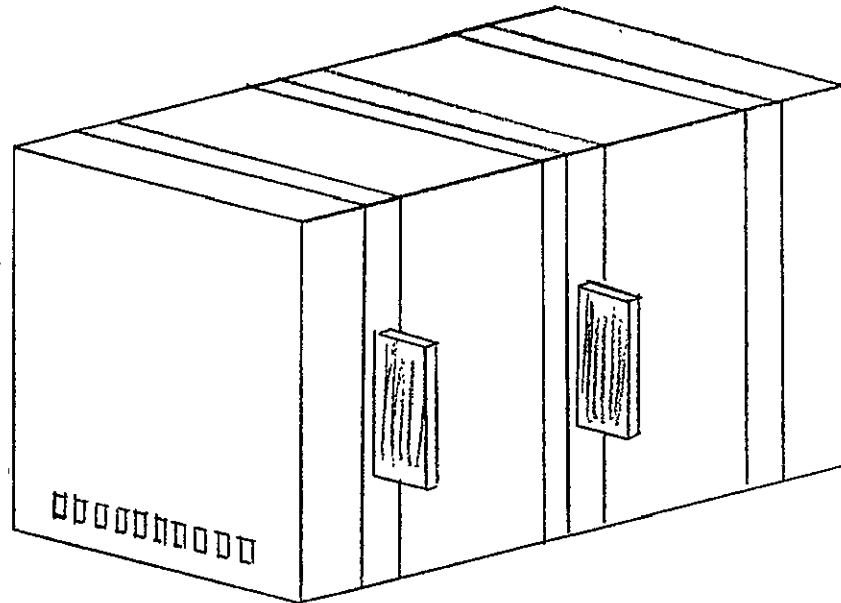


Figure 5  
Stack Assembly Detail

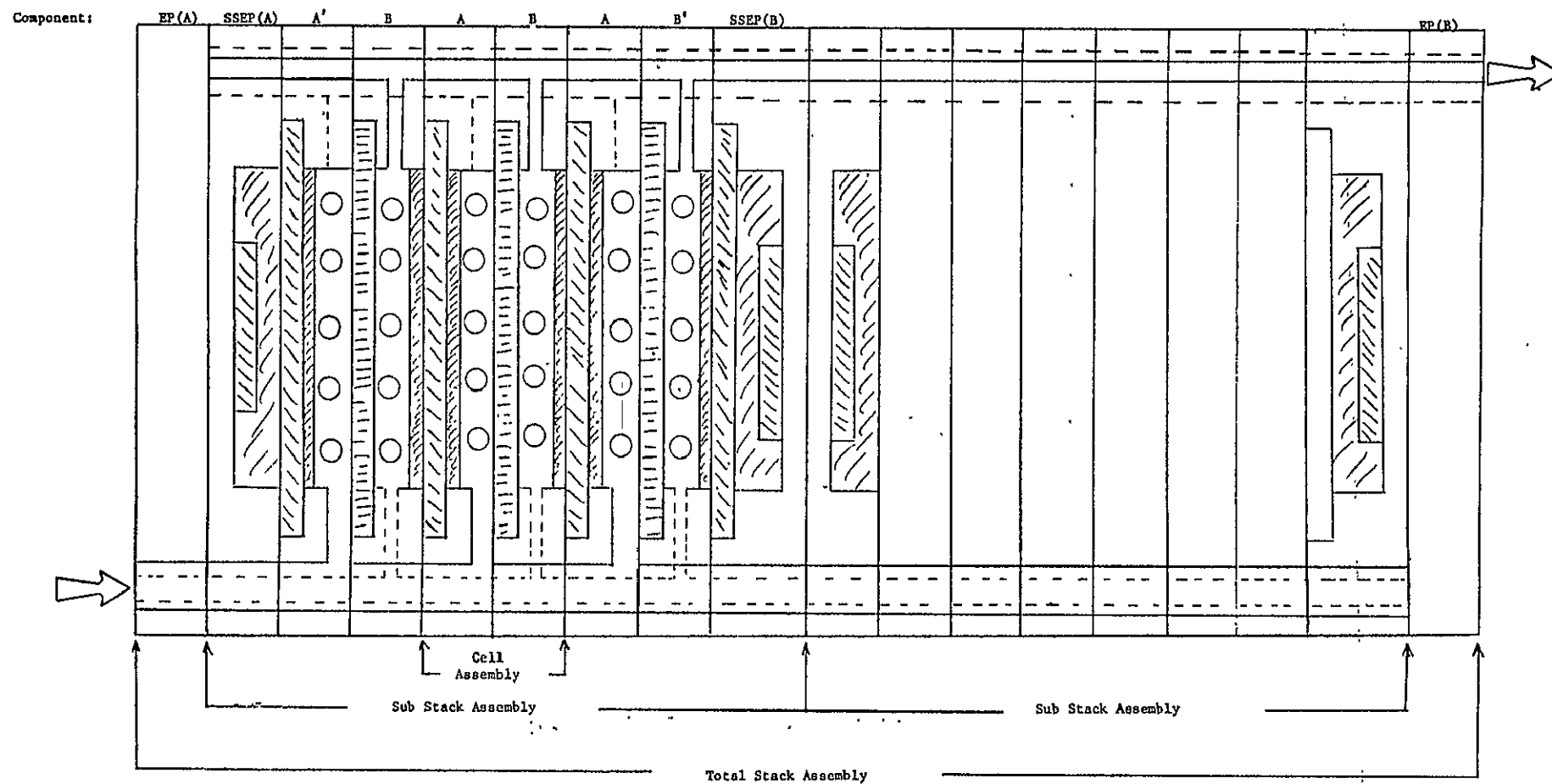
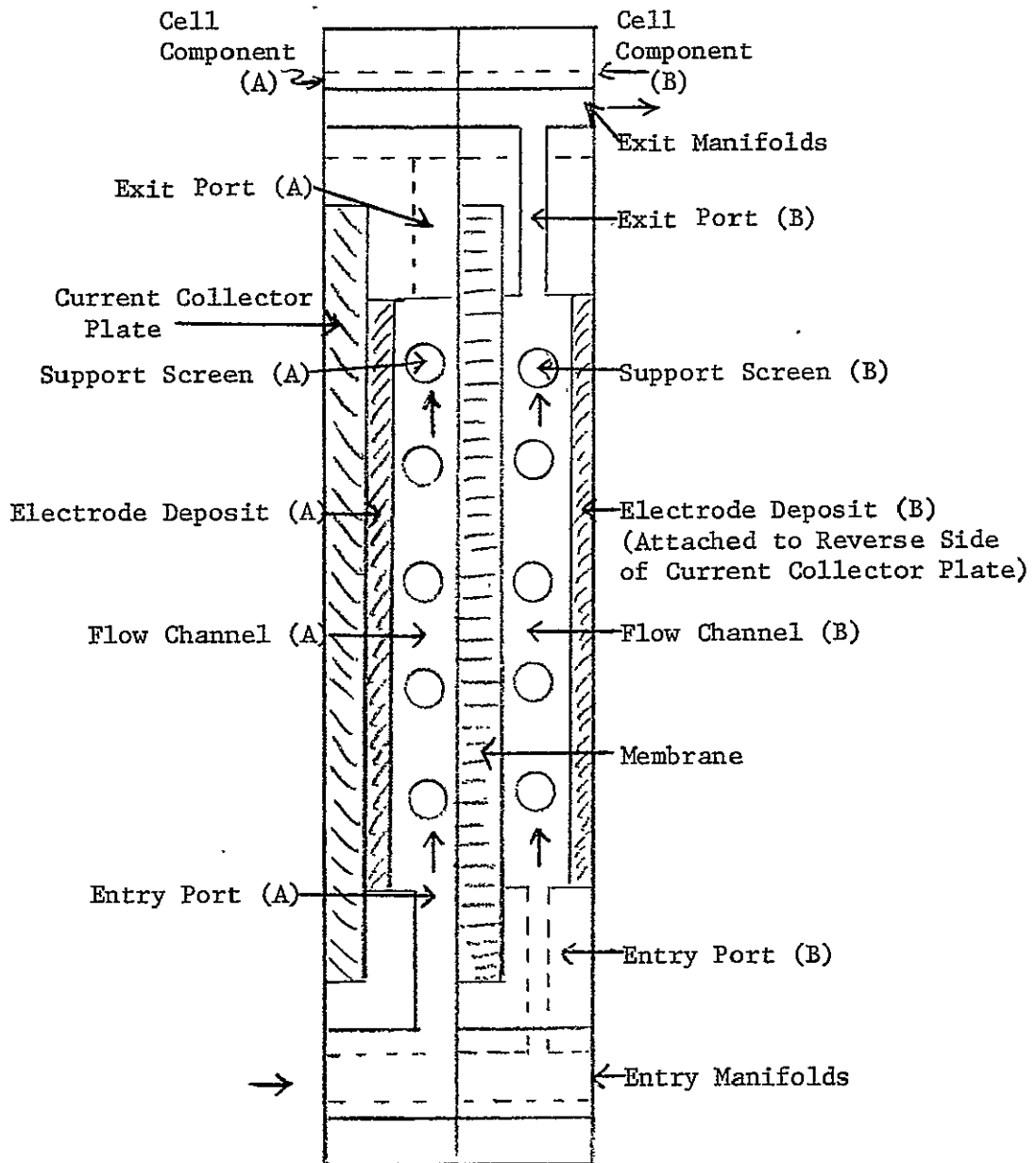


Figure 6Cell Assembly Detail

**Figure 7**  
Cell Component (A)

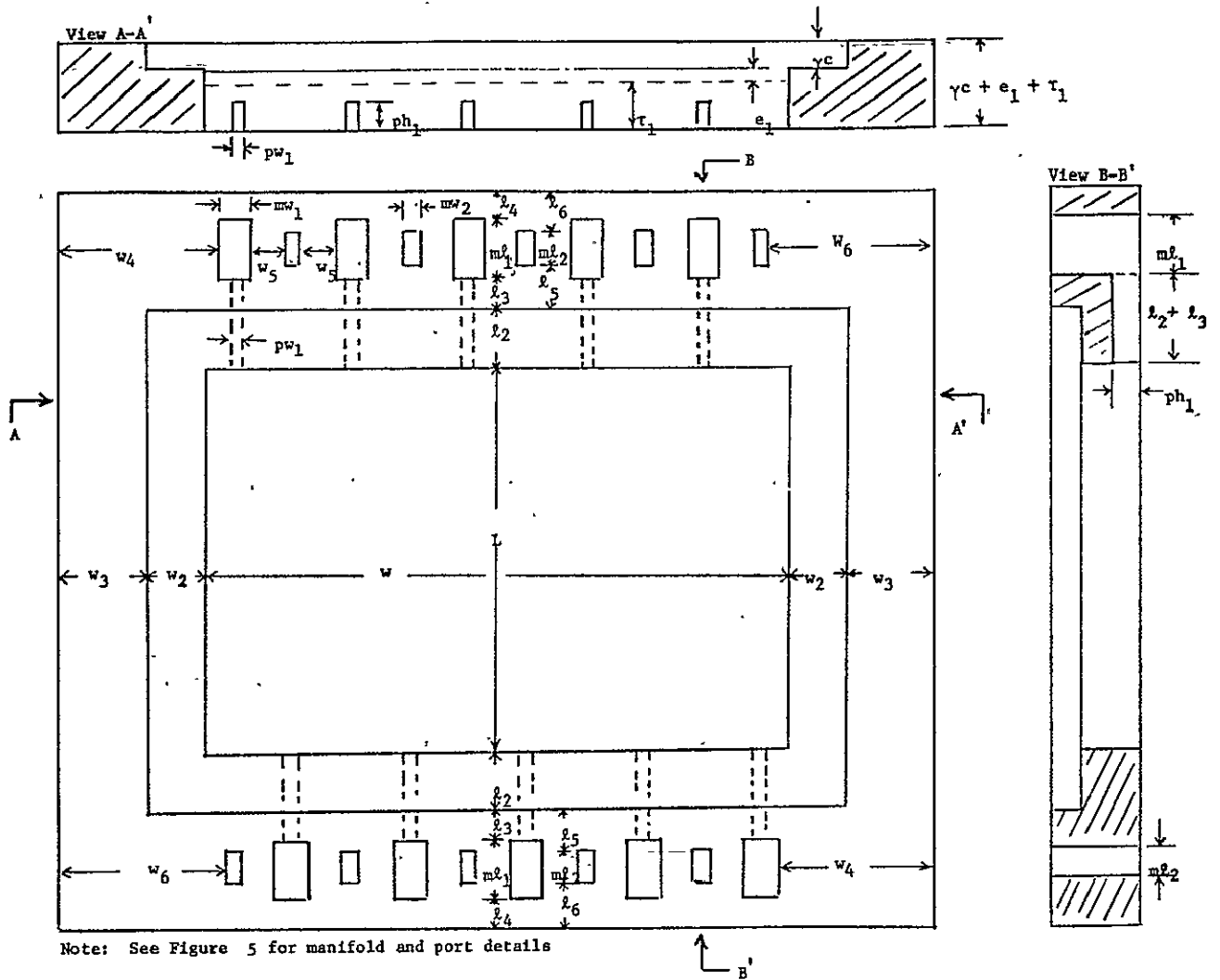


Figure 8  
Manifold and Port Details

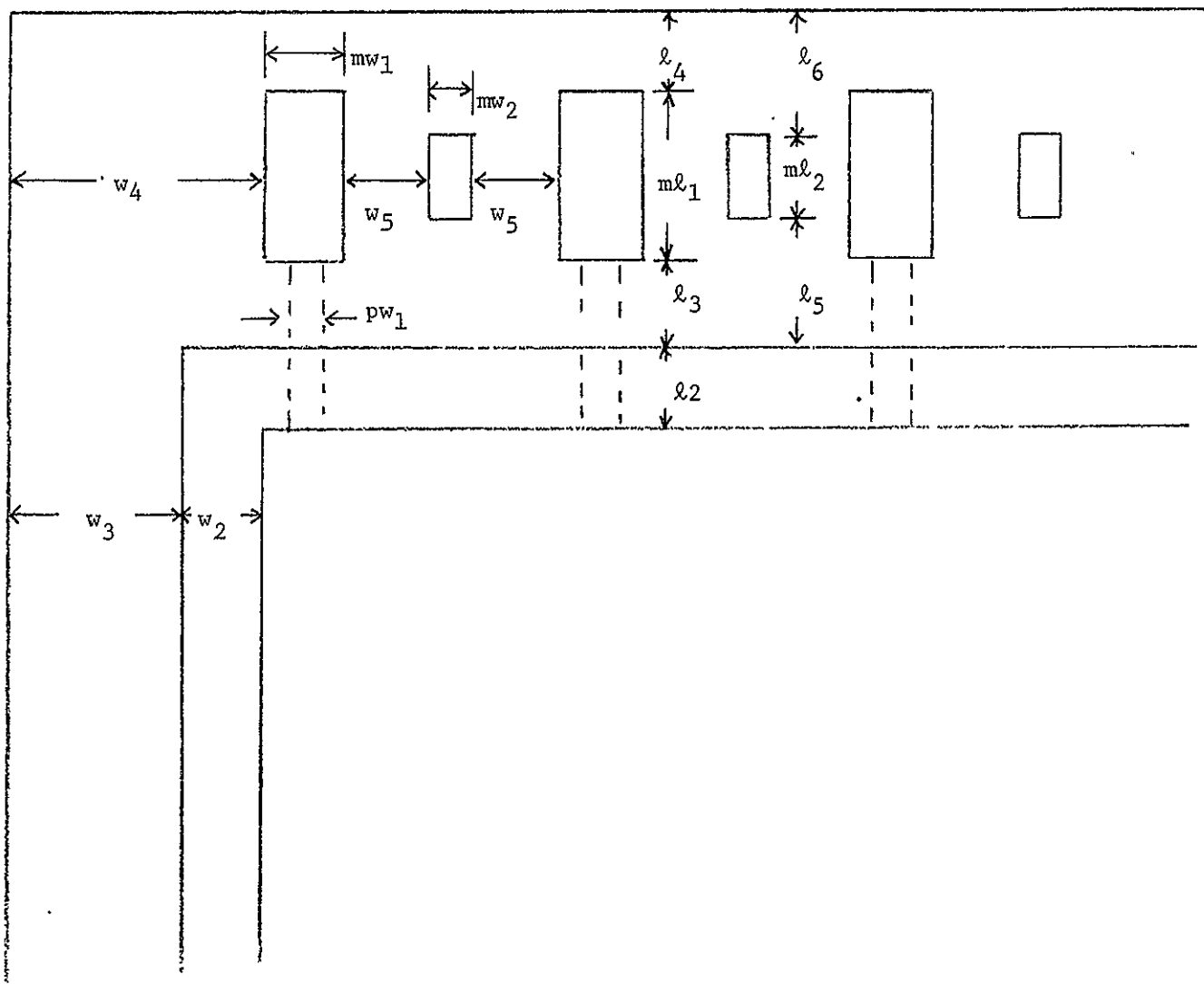




Figure 9

Cell Component (B)

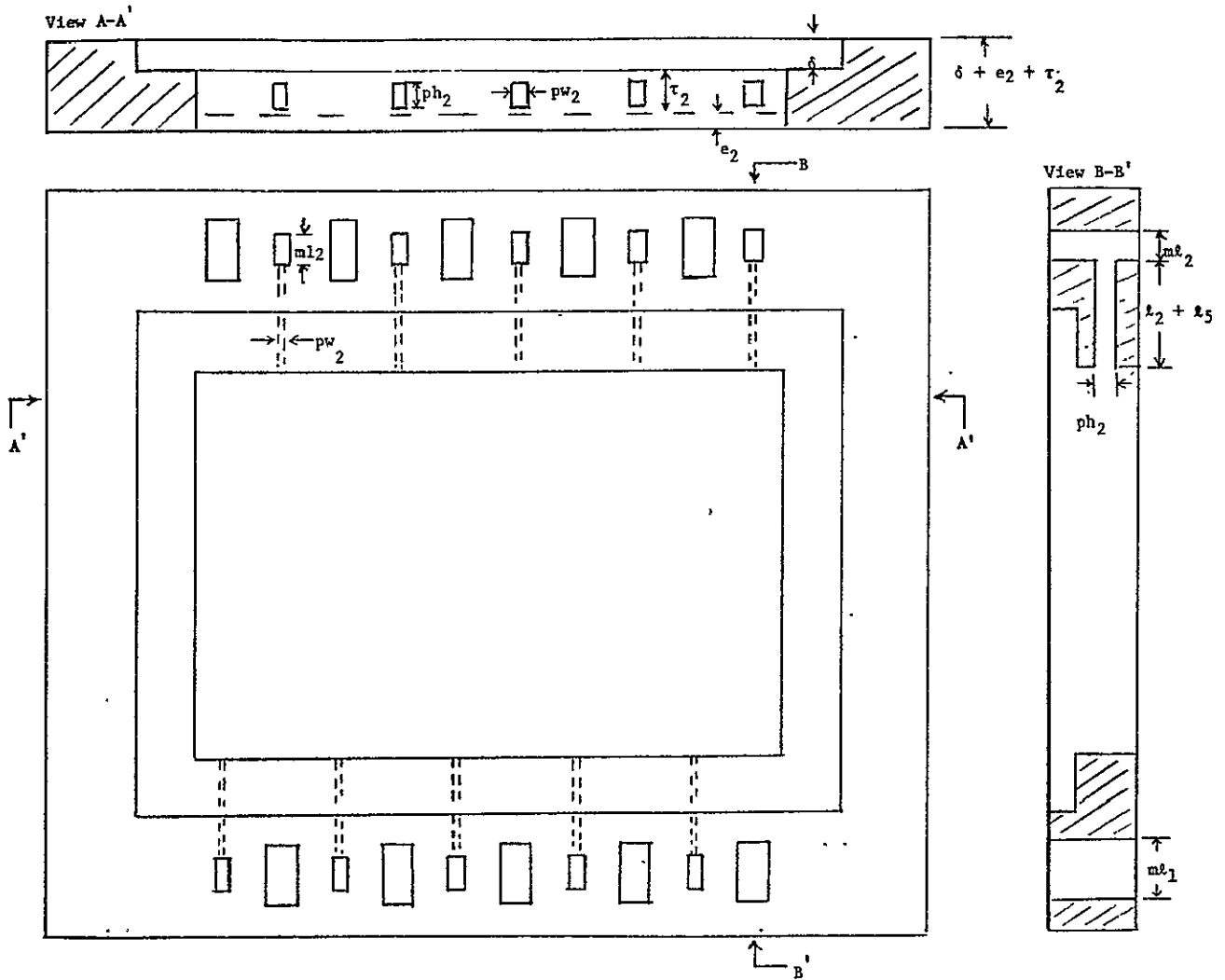


Figure 10  
Sub Stack End Plates (SSEP)

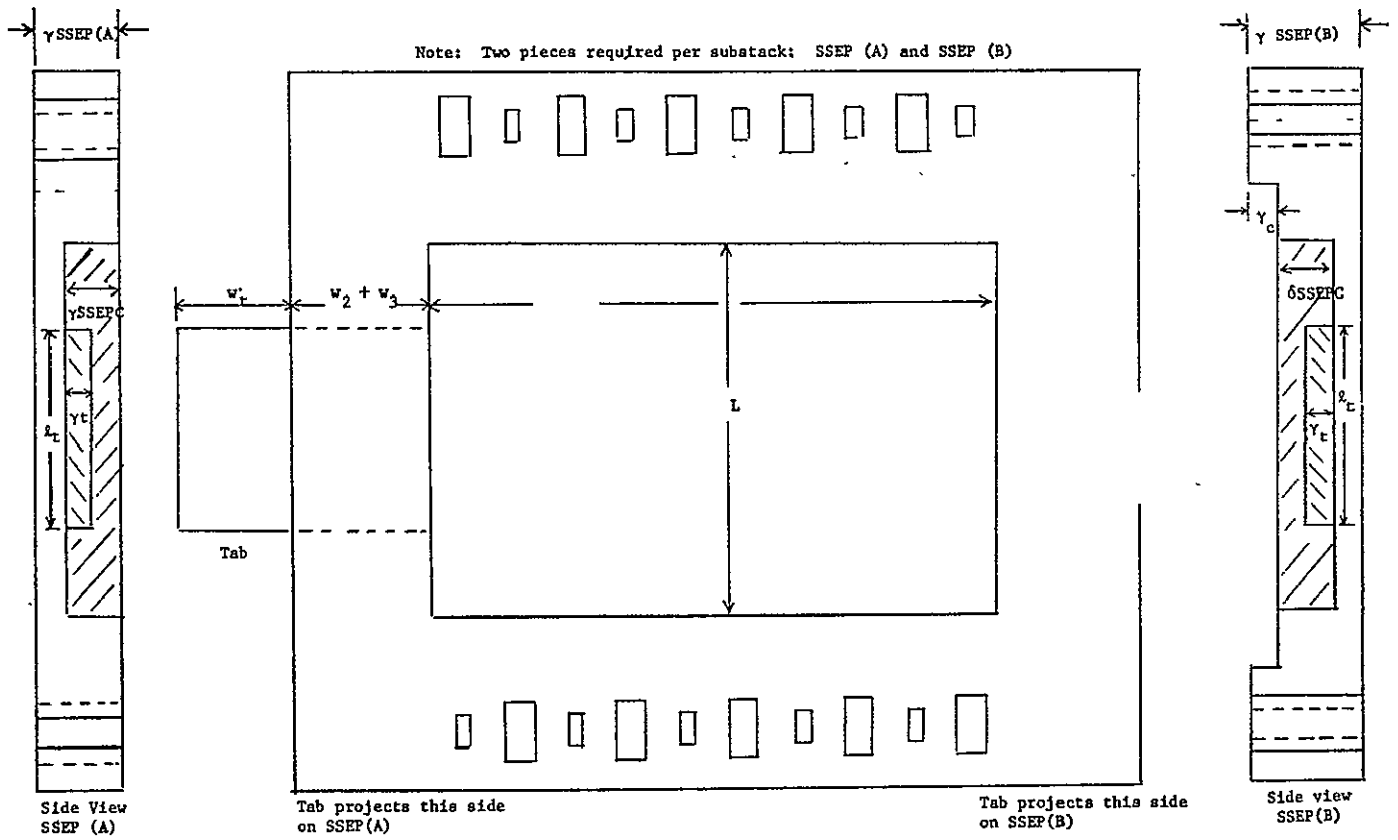


Figure 11  
Stack End Plates

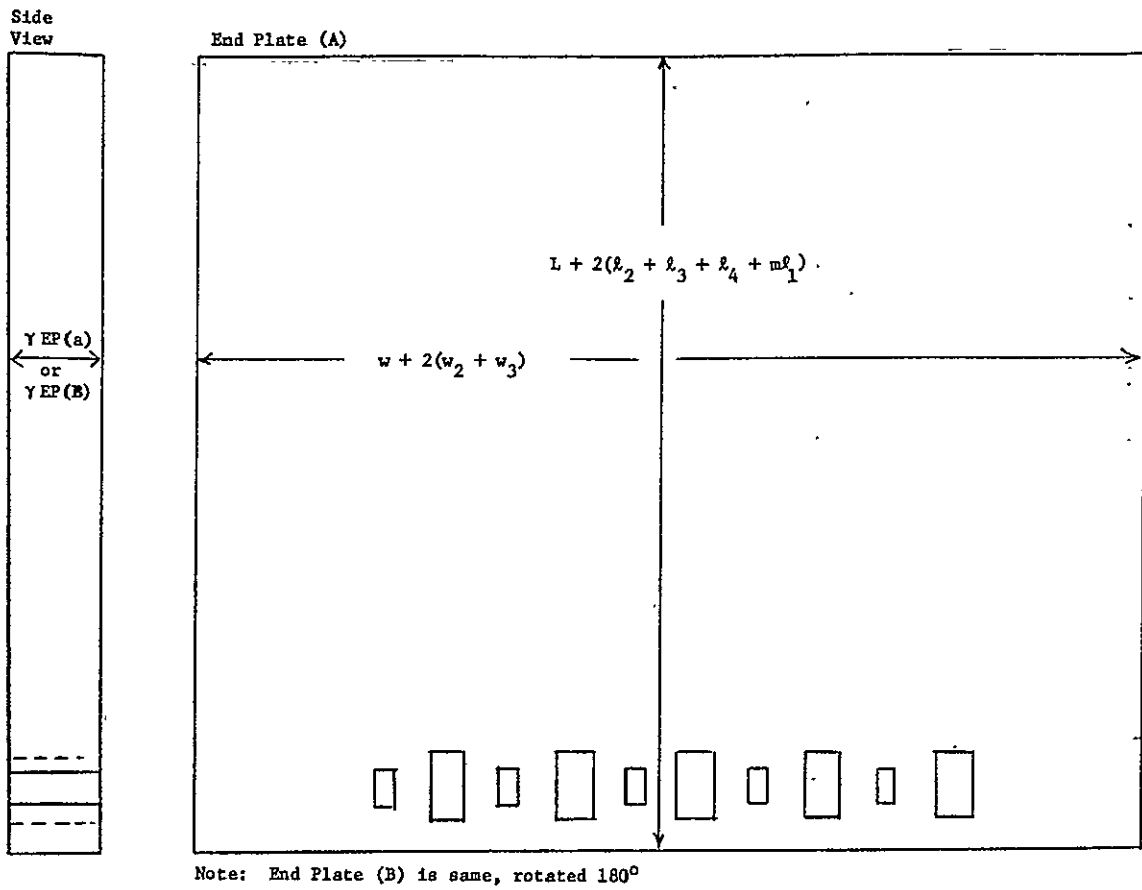


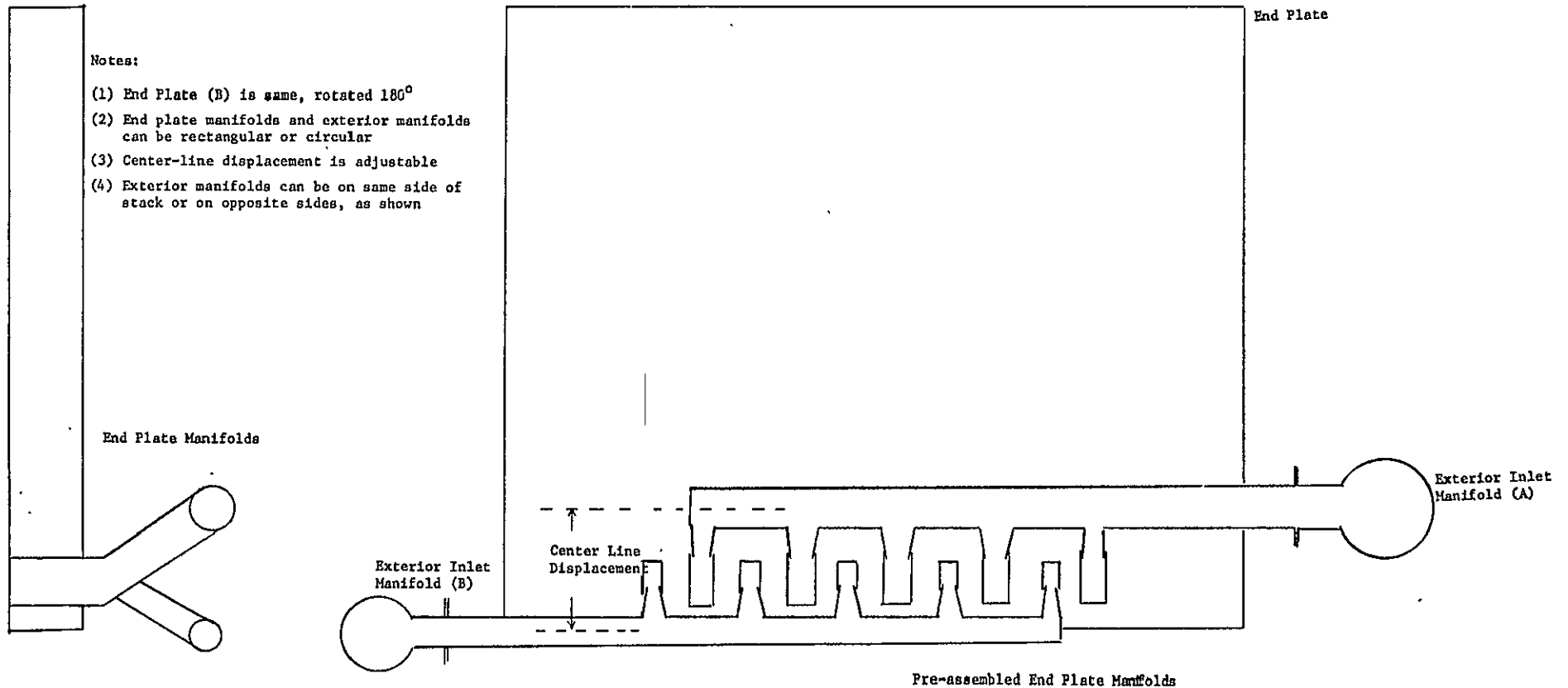
Figure 12Exterior Manifold Connections to End Plate

Table 3Consistency Checks for Cell and Stack Design

## • Width check

$$\omega + 2(\omega_2 + \omega_3) = \omega_4 + \omega_6 + (nm_1)(m\omega_1) + (nm_2)(m\omega_2) + (nm_1 + nm_2 - 1)\omega_5$$

## • Length check

$$L + 2[\ell_2 + \ell_3 + \ell_4 + m\ell_1] = L + 2[\ell_2 + \ell_5 + \ell_6 + m\ell_2]$$

## • Port Placement

$$\omega_4 + 1/2 (m\omega_1 - p\omega_1) \geq \omega_2 + \omega_3$$

$$\omega_6 + 1/2 (m\omega_2 - p\omega_2) \geq \omega_2 + \omega_3$$

## • Port Dimensions

$$p\omega_1 \leq m\omega_1 \quad ph_1 \leq \tau_1$$

$$p\omega_2 \leq m\omega_2 \quad ph_2 \leq \tau_2$$

## • Tab Dimensions

$$\omega_T < 1/2 \delta_{sw}$$

$$\gamma_T \leq \gamma_{SSEPC}$$

$$\ell_T \leq L$$

## • Substack End Plate Dimensions

$$\gamma_{SSEPC} \leq \gamma_{SSEP(A)}$$

$$\gamma_{SSEPC} + \gamma_c \leq \gamma_{SSEP(B)}$$

## • Suggested Dimension Constraints

$$\omega_5 \geq 0.3 \text{ cm}$$

$$\omega_3, \ell_4, \ell_6 \geq 1.5 \text{ cm}$$

$$\omega_2, \ell_2 \geq 0.5 \text{ cm}$$

$$\ell_3, \ell_5 \geq 0.3 \text{ cm}$$

+ Calculate volume of substack end plate conductor + tab:

$$v_{\text{SSEPCT}}, \text{ cm}^3 = \omega L \gamma_{\text{SSEPC}} + (\omega_T + \omega_2 + \omega_3) l_T \gamma_T$$

+ Calculate volume of cell frame plastic (A):

$$\begin{aligned} v_{\text{CFPA}}, \text{ cm}^3 &= [\omega + 2(\omega_2 + \omega_3)] [L + 2(l_2 + l_3 + l_4 + ml_1)] [\gamma_c + e_1 + \tau_1] \\ &\quad - \omega L(e_1 + \tau_1) - (\omega + 2\omega_2)(L + 2l_2)\gamma_c \\ &\quad - 2[(nm_1)(m\omega_1)(ml_1) + (nm_2)(m\omega_2)(ml_2)] [\gamma_c + e_1 + \tau_1] \\ &\quad - 2[(nm_1)(p\omega_1)(ph_1)(l_2 + l_3)] \end{aligned}$$

+ Calculate volume of cell frame plastic (B):

$$\begin{aligned} v_{\text{CFPB}}, \text{ cm}^3 &= [\omega + 2(\omega_2 + \omega_3)] [L + 2(l_2 + l_3 + l_4 + ml_1)] [\delta + e_2 + \tau_2] \\ &\quad - \omega L(e_2 + \tau_2) - (\omega + 2\omega_2)(L + 2l_2)\delta \\ &\quad - 2[(nm_1)(m\omega_1)(ml_1) + (nm_2)(m\omega_2)(ml_2)] [\delta + e_2 + \tau_2] \\ &\quad - 2[(nm_2)(p\omega_2)(ph_2)(l_2 + l_5)] \end{aligned}$$

+ Calculate volume of current collector plate:

$$v_{\text{CCP}}, \text{ cm}^3 = (\omega + 2\omega_2)(L + 2l_2)\gamma_c$$

+ Calculate volume of electrode deposits A and B:

$$v_{\text{EDA}}, \text{ cm}^3 = \omega L e_1$$

$$v_{\text{EBD}}, \text{ cm}^3 = \omega L e_2$$

+ Calculate membrane area:

$$a_m, \text{ cm}^2 = (\omega + 2\omega_2)(L + 2l_2)$$

+ Calculate support screen (A) and (B) area:

$$a_{\text{SSA}}, \text{ cm}^2 = \omega L, \text{ with thickness to match } \tau_1$$

$$a_{\text{SSB}}, \text{ cm}^2 = \omega L, \text{ with thickness to match } \tau_2$$

• Stack Cost

+ Calculate end plate cost:

$$c_{EPP}, \$ = \frac{\rho_{EPP} \cdot c_{EPP}}{10^3} \left[ v_{EPPA} + v_{EPPB} \right]$$

+ Calculate substack end plate cost:

$$c_{SSEP}, \$ = \frac{n_{SS} \rho_{SSEPP} c_{SSEPP}}{10^3} \left[ v_{SSEPA} + v_{SSEPB} \right] \\ + \frac{2 n_{SS} \rho_{SSEPCT} c_{SSEPCT} v_{SSEPCT}}{10^3}$$

+ Calculate cell cost:

$$c_C, \$ = \frac{[n_{SS}(n_S+1)]}{10^3} \left[ \rho_{CCP} \cdot c_{CCP} v_{CCP} \right] \\ + n_{SS} n_S \left[ \frac{\rho_{CFP} c_{CFP} (v_{CFPA} + v_{CFPB})}{10^3} + \frac{\rho_{EDA} c_{EDA} v_{EDA}}{10^3} + \frac{\rho_{EDB} c_{EDB} v_{EDB}}{10^3} \right. \\ \left. + \frac{(a_m c_m + a_{SSA} c_{SSA} + a_{SSB} c_{SSB})}{10^4} \right]$$

+ Calculate stack materials cost:

$$c_{ST, MATL}, \$ = c_{EPP} + c_{SSEP} + c_C$$

+ Calculate stack manufactured cost:

$$c_{ST, MANUF}, \$ = f_m c_{ST, MATL}$$

- Stack Dimensions

+ Calculate stack length:

$$L_S, \text{ cm} = \gamma_{EP(A)} + \gamma_{EP(B)} + n_{SS}(\gamma_{SSEP(A)} + \gamma_{SSEP(B)}) \\ + n_{SS}n_S(\gamma_c + \delta + e_1 + e_2 + \tau_1 + \tau_2)$$

+ Calculate stack width (ex tab projections):

$$W_S, \text{ cm} = \omega + 2 (\omega_2 + \omega_3)$$

+ Calculate stack height

$$H_S, \text{ cm} = L + 2 (\ell_2 + \ell_3 + \ell_4 + m\ell_1)$$

+ Calculate active cell area per stack:

$$A_S, \text{ cm}^2 = n_{SS} n_S L\omega$$



• Trailer Assembly

+ Calculate apparent stack dimensions (including clearance):

- Length:  $L_{SA}, \text{ cm} = L_S + 2\delta_{SL}$

- Width :  $W_{SA}, \text{ cm} = W_S + 2\delta_{SW}$

- Height:  $H_{SA}, \text{ cm} = H_S + 2\delta_{SH}$

+ Calculate number of stacks in vertical direction within trailer (equivalent to number of "decks" per trailer):

$$N_{SH} = \frac{30.48 H_T - 2\Delta_T}{H_S + 2\delta_{SH}}, \text{ rounded to lower integer value}$$

+ Calculate planar deck configuration. Consider 2 versions, with  $L_{SA}$  and  $W_{SA}$  interchanged. Rounding procedure could yield a configuration with maximum number of stacks per deck:

- Configuration A:

Number of stacks on deck in horizontal direction:

$$N'_{SW} = \frac{30.48 W_T - 2\Delta_T}{W_S + 2\delta_{SW}}, \text{ rounded to lower integer}$$

Number of stacks on deck in lengthwise direction:

$$N'_{SL} = \frac{30.48 L_T - 2\Delta_T}{L_S + 2\delta_{SL}}, \text{ rounded to lower integer}$$

- Configuration B:

$$N''_{SW} = \frac{30.48 W_T - 2\Delta_T}{L_S + 2\delta_{SL}}, \text{ rounded to lower integer}$$

$$N''_{SL} = \frac{30.48 L_T - 2\Delta_T}{W_S + 2\delta_{SW}}, \text{ rounded to lower integer}$$

- Calculate  $(N'_{SW})$   $(N'_{SL})$  and  $(N''_{SW})$   $(N''_{SL})$ . Select configuration, A or B, yielding maximum value of product (maximum number of stacks per deck). Call resulting values  $N_{SW}$  and  $N_{SL}$ .

- + Calculate number of stacks in trailer:

$$N_{ST} = N_{SH} N_{SW} N_{SL}$$

- + Calculate total active cell area in trailer:

$$A_T, \text{ cm}^2 = N_{ST} A_S$$

• Trailer Electrical Connection

- + Calculate stack output:

- Stack voltage:  $V_S, \text{ volts} = n_S E_c$

- Stack current:  $I_S, \text{ amps} = n_{SS} \bar{i} \omega L$

Note that:  $n_S$  = number of cells in a substack, connected electrically in series

$n_{SS}$  = number of substacks in a stack, connected electrically in parallel.

- + Calculate trailer output:

- Option A: All stacks in trailer connected in series

Trailer Voltage:  $V_T, \text{ volts} = N_{SH} N_{SW} N_{SL} n_S E_c$

Trailer Power :  $P_T, \text{ MW} = p_c A_T 10^{-6}$

- Option B: All stacks in one deck connected in series, decks connected in parallel

Trailer Voltage:  $V_T, \text{ volts} = N_{SW} N_{SL} n_S E_c$

Trailer Power : as above.

- Trailer Installation

During course of power cycle analysis, keep track of maximum absolute values of  $P_T$  and associated  $V_T$ . Label these  $P_{T \text{ MAX}}$  and  $V_{T \text{ MAX}}$ . Note that maximum value could occur during charge or discharge operation.

+ Calculate trailer manufactured cost:

$$C_{T, \text{MANUF}, \$} = N_{ST} C_{ST, \text{MANUF}} + P_{T \text{ MAX}} \left[ C_{TP} + C_{TBB} + C_{TS} + C_{TI} \right] 10^3$$

+ Calculate trailer installed cost:

$$C_{T, \text{INSTAL}, \$} = C_{T, \text{MANUF}} + C_I P_{T \text{ MAX}} 10^3$$

+ Calculate installed cost of complete Redox converter subsection:

$$C_{T, \text{TOTAL INST}, \$} = N_T C_{T, \text{INSTAL}}$$

### Power Conditioning Section

The approach used to size and cost the power conditioning section is identical to that used in the Stage 1 Model (page 1-6 of the Stage 1 Model Documentation). The maximum input power level and associated voltage to the power conditioning section during the total operating period in the Stage 2 Model is stored and used to size and cost the power conditioner.

### Tankage Section

The gross volumes of stored reactant solution are input parameters in the Stage 2 Model. Useful or net volumes are calculated using the tank ullage and liquid hold-up factors described in the Stage 1 Model documentation (Page 1-7). Tankage costs are calculated directly from the input values. Optional use of smaller multiple tanks for each reactant is permitted in the Stage 2 Model.

### Pump Section and Filter Section

The pump and filter sizing and costing routines in the Stage 2 Model are identical to those used in the Stage 1 Model Documentation (page 1-8 and 1-9). Again, the maximum flow rates noted during the operating period of the Stage 2 Model are used.

### Cooler (Heat Exchanger) Section

Thermal effects associated with Redox cell operation are estimated during each  $\Delta t$  time slice. The Stage 1 Model approach is used, resulting in an instantaneous value of cooler fan horsepower consumption. Coolers are sized and costed on the basis of the maximum duty noted during the complete weekly

cycle. Note that we assume thermal balance at all times. Thermal effect carry-over into the storage tank system is neglected.

• Heat Generation Rate:

From the Stage 1 Model:

$$+ \text{ Heat generated during discharge, } Q_D = S_{1D} E_{FD} Z_1 F \left[ \frac{v_R}{E_{FD} E_T} - v_D \right]$$

$$+ \text{ Heat generated during charge, } Q_C = \frac{S_{1C} Z_1 F}{E_{FC}} \left[ v_C - v_R \left( \frac{E_{FC}}{E_T} \right) \right]$$

These forms are modified by substituting appropriate Stage 2 Model variables:

$$Q_D = \bar{i}(\omega L) (n_{SS} \ n_S) N_{ST} \ N_T \left[ \frac{\phi_R}{E_{FD} E_T} - E_C \right]$$

$$Q_C = -\bar{i}(\omega L) (n_{SS} \ n_S) N_{ST} \ N_T \left[ E_C - \phi_R \left( \frac{E_{FC}}{E_T} \right) \right]$$

Here,  $\phi_R$  = reversible cell voltage at time  $t$  and  $E_C$  is the consistent value of cell voltage derived from the nested loop calculations carried out during a time interval  $\Delta t$ . These  $Q$  values are converted to MW units, and then used as entry values in the Stage 1 Model routines (Documentation, Page 1-10). During each time period,  $Q_{COOL(1)}$  and  $Q_{COOL(2)}$  are calculated, followed by the exchanger plot areas,  $PA(1)$  and  $PA(2)$ , and the corresponding fan horsepower,  $\pi(1)$  and  $\pi(2)$ . The latter are used to calculate an instantaneous value of auxiliary power in the nested loop sequence. The maximum value of plot area calculated during a weekly cycle is used to cost the cooler facility.

This approach to system thermal balance presupposes that each packet of reactant solution enters at a fictitious value of  $T_{STORAGE}$  (Documentation, Page 1-10). In reality, if the system load changes rapidly, there will be a varying output temperature. This will feed back to the storage tanks and result in varying, not constant, inlet temperatures. Addition of a thermal monitoring subroutine is not justified at this time.

Stored Solution Costs

The Stage 1 procedure for costing the stored solution (reactant plus supporting electrolyte) inventory is used (Documentation, page 1-11).

# Attachment 1

## Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
● Cell Frame Dimensions				
w	Active cell width	W	cm ↓	5-100
w <sub>2</sub>	Side zone width	W <sub>2</sub>		0.1-10
w <sub>3</sub>	↓	W <sub>3</sub>		↓
w <sub>4</sub>	Manifold zone width	W <sub>4</sub>		↓
w <sub>5</sub>	↓	W <sub>5</sub>		↓
w <sub>6</sub>	↓	W <sub>6</sub>		↓
L	Active cell length	L		5-100
l <sub>2</sub>	Manifold zone length	L <sub>2</sub>		0.1-10
l <sub>3</sub>	↓	L <sub>3</sub>		↓
l <sub>4</sub>	↓	L <sub>4</sub>		↓
l <sub>5</sub>	↓	L <sub>5</sub>		↓
l <sub>6</sub>	↓	L <sub>6</sub>		↓
● Manifold Dimensions				
nm <sub>1</sub>	Number of manifolds	NM1	--	1-500
nm <sub>2</sub>	↓	NM2	--	↓
mω <sub>1</sub>	Manifold width	XMNW1	cm	0.1-5
mω <sub>2</sub>	↓	XMNW2	↓	↓
ml <sub>1</sub>	Manifold Length	XMNL1	↓	↓
ml <sub>2</sub>	↓	XMNL2	↓	↓

# Attachment 1 (CONT'D)

## Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
● Port Dimensions				
$np_1$	Number of ports <sup>(1)</sup>	NP1	--	1-500
$np_2$	↓	NP2	--	↓
$p\omega_1$	Port width	PW1	cm	0.1-5
$p\omega_2$	↓	PW2	↓	↓
$ph_1$	Port height	PH1	↓	↓
$ph_2$	↓	PH2	↓	↓
● Cell Component Dimensions				
$\gamma_c$	Current collector plate thickness	GC	cm	0.1-5
$\delta$	Membrane thickness	DELTA	↓	0.0001-0.01
$e_1$	Electrode deposit thickness	E1	↓	0-1
$e_2$	↓	E2	↓	↓
$\tau_1$	Flow zone thickness	TAU1	↓	↓
$\tau_2$	↓	TAU2	↓	↓
● SubStack End Plate Dimensions				
$\gamma_{SSEP(A)}$	Overall thickness	GSSEPA	cm	0.1-5
$\gamma_{SSEP(B)}$	↓	GSSEPB	↓	↓
$\gamma_{SSEPC}$	Conductive section thickness	GSSEPC	↓	↓
$\gamma_T$	Tab thickness	GT	↓	↓
$\ell_T$	Tab length	LT	↓	5-100
$\omega_T$	Tab width	WT	↓	1-20

(1) This program assumes  $np_1=nm_1$  and  $np_2=nm_2$ , so that there is one port hole per manifold.

Attachment 1 (CONT'D)

Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
• End Plate Dimensions				
$\gamma_{EP(A)}$	End plate (A) thickness	GEPA	cm	0.5-3
$\gamma_{EP(B)}$	End plate (B) thickness	GEPB	↓	↓
• Density of Cell and Stack Materials				
EPP	End plate plastic (A&B) density	REPP	gms/cm <sup>3</sup>	0.3-3
SSEPP	Substack end plate plastic (A&B) density	RSEPP	↓	↓
SSEPCT	Substack end plate conductor and tab density	RSEPCT	↓	↓
CFP	Cell frame plastic (A&B) density	RCFP	↓	↓
CCP	Current collector plate density	RCCP	↓	↓
EDA	Electrode deposit density (A)	REDA	↓	↓
EDB	↓ (B)	REDB	↓	↓
• Cost of Cell and Stack Materials				
$c_{EPP}$	End plate plastic (A&B) cost	CEPP	\$/kg	0.1-20
$c_{SSEPP}$	Substack end plate plastic (A&B) cost	CSEPP	↓	↓
$c_{SSEPCT}$	Substack end plate conductor and tab cost	CSEPCT	↓	↓
$c_{CFP}$	Cell frame plastic (A&B) cost	CCFP	↓	↓
$c_{CCP}$	Current collector plate cost	CCCP	↓	↓
$c_{EDA}$	Electrode deposit cost (A)	CEDA	↓	↓
$c_{EDB}$	(B)	CEDB	↓	↓
$c_{SSA}$	Support screen cost (A)	CSSA	\$/m <sup>2</sup>	↓
$c_{SSB}$	(B)	CSSB	↓	↓
$c_M$	Membrane cost	CM	↓	↓



Attachment 1 (CONT'D)

Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
• Cell, Stack and Trailer Assembly Factors				
$n_S$	Number of cells per sub stack	NS	--	5-100
$n_{SS}$	Number of sub stacks per stack	NSS	--	1-20
$f_m$	Stack fabrication cost factor	FM	--	2-3
$\delta_{SW}$	Stack installation clearance, width	DELTAW	cm	20-40
$\delta_{SH}$	Same, height	DELTAH	↓	10-30
$\delta_{SL}$	Same, length	DELTAL		20-40
$T_H$	Shippable trailer external height	HTUS	ft	10
$T_W$	Same, width	WTUS	↓	10
$T_L$	Same, length	LTUS		40
$\Delta_T$	Trailer inboard clearance	DELTAT	cm	20-40
$C_{TP}$	Cost of trailer internal piping	CTP	↓	5-15
$C_{TBB}$	Cost of trailer bus bar + electricals	CTBB		5-20
$C_{TS}$	Cost of trailer structurals	CTS		5-15
$C_{TI}$	Cost of trailer instrumentation	CTI		5-15
$C_I$	Cost of trailer installation	CI		15-30
$C_{PCI}$	Cost of power conditioner installation	CPCI	↓	15-30

# Attachment 1 (CONT'D)

## Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
• System Efficiency Factors				
$E_R$	AC to DC rectifying efficiency	ER	--	0.9-0.98
$E_I$	DC to AC inversion efficiency	EI	--	0.9-0.98
$E_T$	Cell thermal efficiency	ET	--	0.8-1.2
$E_{FC}$	Faradaic efficiency during charge	EFC	--	0.8-1.0
$E_{FD}$	Same, during discharge	EFD	--	0.8-1.0
• System Operational Factors				
$f_1, f_2$	Solution flow rate factor	F1, F2	--	1-50
$f_P$	Pump power factor	FP	--	0.2-1
$E_{MAX}$	Maximum permitted cell voltage	EMAX	Volts	1-2
$(\beta_1)_{MAX}, (\beta_2)_{MAX}$	Reactant utilization factor, upper concentration limit	B1 MAX, B2 MAX	--	0.6-1.0
$(\beta_1)_{MIN}, (\beta_2)_{MIN}$	Same, lower limit	B1 MIN, B2 MIN	--	0-0.4
$T_{CELL}$	Redox converter operating temperature	TCELL	°C	25-80
$T_{AIR}$	Ambient air temperature	TAIR	°C	5-40
$f_I(1), f_I(2)$	Solution inventory factor	FI1, FI2	--	1.0-1.1
$f_{TU}(1), f_{TU}(2)$	Tank ullage factor	FTU1, FTU2	--	1.0-1.2
$N_T$	Number of redox trailers	NT	--	--
$V_T(1), V_T(2)$	Gross solution inventory	VT1, VT2	bb1	--
$N_{TANK}(1), N_{TANK}(2)$	Number of tanks per reactant	NTANK 1, NTANK 2	--	--

Attachment 1 (CONT'D)

Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
● Reactant Properties				
$Z_1, Z_2$	Electrons transferred per mole	Z1, Z2	eq/gm mole	1-3
$E_1^o, E_2^o$	Reaction standard potential	E10, E20	volts.	-0.5-2
$(i_o)_1, (i_o)_2$	Exchange current density	I10, I20	amps/cm <sup>2</sup>	$10^{-6}$ - $10^{-2}$
$\alpha_1^+, \alpha_2^+$	Reaction transfer coefficient	ALFA1L, ALFA2L	--	--
$\alpha_1^-, \alpha_2^-$	Same	ALFA1R, ALFA2R	--	--
$C_1, C_2$	Initial reactant concentration	C1, C2	gm moles/liter	1-5
$\bar{\rho}_{SOL(1)}, \bar{\rho}_{SOL(2)}$	Average solution density, reactant + electrolyte	RHO1, RHO2	gm/cm <sup>3</sup>	1-2
$\bar{C}_{P1}, \bar{C}_{P2}$	Average solution heat capacity	CPL, CP2	cal/gm °C	0.7-1.0
$C_R(1), C_R(2)$	Delivered cost of reactant solutions	CR1, CR2	\$/kg	0.5-10
$MW_1, MW_2$	Reactant mol. wt. (complete compound)	MW1, MW2	gms/gm mole	75-250
$\mu_1, \mu_2$	Solution viscosity	VISC1, VISC2	poise	0.005-0.05
$D_1, D_2$	Reactant diffusivity	D1, D2	cm <sup>2</sup> /sec	$10^{-4}$ - $10^{-7}$
$\rho_{E(1)}, \rho_{E(2)}$	Solution resistivity	RHOE1, RHOE2	ohm cm	0.5-10

Attachment 1 (CONT'D)

Parameters in Stage 2 Model

<u>Symbol</u>	<u>Definition</u>	<u>Computer Program Notation</u>	<u>Units</u>	<u>Suggested Range of Parameter Values</u>
• Electrode Deposit Properties				
$e_1, e_2$	Deposit thickness	E1, E2	cm	0.01-0.1
$\epsilon_1, \epsilon_2$	Void fraction	EPS1, EPS2	--	0.2-0.7
$f_{C1}, f_{C2}$	Coverage accessibility factor	FC1, FC2	---	0.8-1.0
$\sigma_1, \sigma_2$	Intrinsic catalyst surface area	SIGMA1, SIGMA2	m <sup>2</sup> /gm	20-1000
$q_1, q_2$	Tortuosity factor	QQ1, QQ2	--	1.4-2
$\rho_{SOLID(1)}, \rho_{SOLID(2)}$	Intrinsic catalyst density	RHOS1, RHOS2	gms/cm <sup>3</sup>	1-20
• Supporting Electrolyte Properties				
$C_{1S}, C_{2S}$	Supporting electrolyte concentration	C1S, C2S	gm moles/liter	1-10
$MW_{SE}$	Mol. wt. of supporting electrolyte	MWSE	gms/gm mole	30-150
$C_{SE}$	Delivered cost of supporting electrolyte	CSSE	\$/kg	0.1-1.0
• Miscellaneous Factors				
$\rho$	Membrane resistivity	RHO	ohm cm	10-100
$\psi_1, \psi_2$	Mass transfer augmentation factors	PSI1, PSI2	--	0.5-10

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